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RADC-TR-67-108, Volume I
Final Report

RADC RELIABILITY NOTEBOOK
VOLUME I

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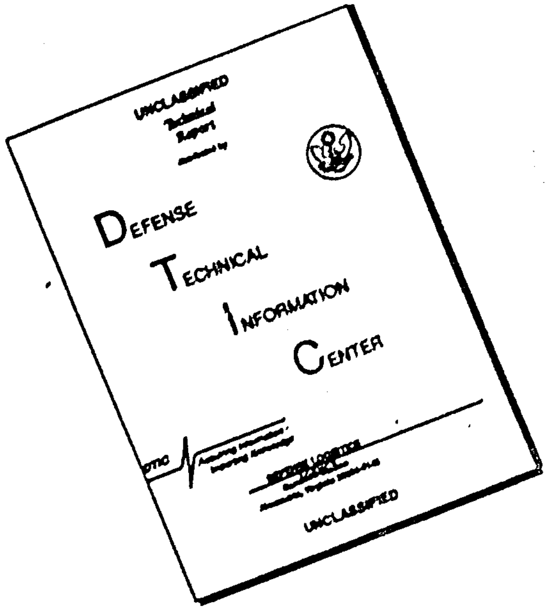

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FOREWORD

This technical report was prepared for RADC by Computer Applications Incorporated, 555 Madison Avenue, New York, N.Y. 10022, under Contract F30602-67-C-0139, Project No. 5519, Task No. 551902, covering the period from December 1966 to June 1968. The authors of this report were Fred Mazzilli, John Mathis, Richard Schwartz, and Dr. Samuel Shapiro.

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Distribution of this report is limited by the Mutual Security Acts of 1949.

This technical report has been reviewed and is approved.

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ABSTRACT

RADC Reliability Notebook, Volume I, is an updating of the RADC Reliability Notebook which was first published in 1958 and which had been revised several times up until the Fall of 1966. This updating has resulted in a completely updated (except for Section 8) notebook in arrangement, format and material as per the contract under which the effort was conducted. There are twelve chapters comprising, first, a general discussion, followed by a presentation of information which project managers and project engineers can use to be more effective in predicting, measuring and improving system and equipment reliability. A subject index has been included at the end in order to provide the user with a guide to locating specific information.

This updating was based on a major collection of existing information with emphasis on reliability in large system development as well as in non-system or off-the-shelf hardware procurement programs. Emphasis has been placed on prediction techniques; test demonstration plans and analysis of test data; and on the relationship between reliability and various other factors including engineering disciplines, program milestones, design reviews and engineering/acceptance tests covered at length in various Air Force documents such as AFSCM/AFLCM 310-1 and the AFSCM 375 series of publications. Of particular significance is the inclusion of information on Bayesian statistics and the application of this statistical concept to the development of demonstration test plans and the interpretation of test data.

The information presented in this updated version of the RADC Reliability Notebook, together with the references and the guidelines contained in Air Force program management publications, will provide project engineers and project managers with a sound basis for implementing reliability oriented effort and program plans and for monitoring to insure that reliability objectives will be met.

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EVALUATION

1. System project officers, reliability program managers, and others who are responsible for directing system and equipment reliability programs have long expressed their need for a reliability handbook oriented towards reliability program management with attendant coverage of the technical disciplines of reliability engineering. The objective of this effort was the development of such a document, Volume I of the RADC Reliability Notebook.

2. This Volume I is designed to bridge the gap which presently exists between the familiar reliability textbooks and the several reliability management documents currently available such as ESD's Handbook for Reliability and Maintainability Monitors and the NASA two-volume Reliability Management Handbook. The reliability textbooks, of course, provide reliability engineering fundamentals and usually include chapters on reliability prediction, improvement and measurement techniques. The reliability management documents contain material which is primarily administrative and include discussions of the managerial-oriented reliability activities required during system development. Neither, however, make any attempt to describe the relationship between the two subject areas, nor do they convey the dependence of one on the other. Volume I not only contains both administrative and technical reliability information, but also combines the managerial-oriented reliability activities with the technical-oriented information necessary for making decisions on reliability requirements, predictions and tests. Thus, for example, the reliability program manager is not only able to determine at what stage of development a reliability prediction is required, but he is also presented a detailed account of the specific reliability prediction techniques which he can use at that time.

3. The RADC Reliability Notebook, RADC-TR-67-108, now consists of two volumes - this Volume I and Volume II (DDC No. AD-821640) which contains updated part failure rate data and reliability prediction models. Although the material in Volume I is not subject to as rapid change as that in Volume II, revisions and additions will be made when required.

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CHAPTER 1

INTRODUCTION

System Reliability has become a key factor in describing tactical/operational needs and in turn it has become a key characteristic in evaluating system requirements and resultant performance. Tactical requirements have become such that systems are becoming more complex. As a result, reliability requirements become more difficult to meet from a performance point of view as well as from a dollar and schedule point of view. In recognition of this it has become increasingly more apparent that the positive application of reliability engineering techniques and the monitoring of reliability performance, from inception through delivery and follow-up for improvement, can be very effective in helping to ensure that system reliability/performance requirements will be met.

As with other performance characteristics, reliability is a quantitative element and, as such, it can be specified as a requirement, it can be predicted based on available design information, it can be measured through test and performance data, and it can be observed under operation conditions. Because of its quantitative nature, its predictability and measurability, reliability can be monitored and influenced at various stages in the system life cycle. Proper recognition of these features and the application of resources to them, both from an emphasis and timing point of view, can significantly influence the potential for meeting reliability requirements within cost and schedule.

Use of these features and the application of resources oriented toward monitoring, controlling, and influencing reliability must be integrated with various other activities required as part of a system development or equipment procurement program. While reliability is strongly influenced by individual designers, the responsibility for the direction and emphasis, for developing assurances, and planning and devoting resources required to effectively monitor and influence reliability rests with system project officers, reliability managers, and those who are responsible for directing system and equipment reliability programs. The amount of information and knowledge required to make sound decisions in fulfilling these responsibilities is vast and covers a wide range. This range includes administrative oriented techniques, information and requirements for making evaluations, implementing activities and receiving information as well as technically oriented information necessary for making decisions covering requirements, predictions and tests.

This handbook provides information in the administrative areas as well as in the technical area pertinent to guiding its users toward reliability planning and making the reliability-oriented evaluations and decisions which will provide a greater degree of assurance that reliability requirements will be met. It is designed to aid management in reaching decisions concerning reliability aspects of a program throughout the system development cycle or equipment procurement cycle. It outlines techniques and practices as well as Air Force requirements in such a way as to provide guidelines which can be used for making decisions concerning the planning and implementing of pertinent activities.

The first seven chapters of this Volume 1*. of the RADC Reliability Notebook is primarily management or administrative oriented. The information covers reliability program management, reliability engineering management, data management, assuring reliability program effectiveness, and field data. There is considerable tie-in to Air Force documents (which detail various system program requirements) in such a way that reliability can become an integral part of a system program within existing regulations and requirements. Although not altogether exhaustive since such a treatment would become extremely voluminous, the information docs provide the guidance needed to plan and prepare for these reliability oriented activities, controls, and data receivables which meet the requirements of the program at hand.

Chapters 8 through 11 are more technically oriented from the point of view of the application of techniques. The information in these latter chapters covers allocation, prediction, measurement, and improvement. There are examples which can be used as guides in applying the techniques to specific problems. Here again, the information is not completely exhaustive and does not cover extremely complex models. The coverage, however, is sufficient to provide the user with the tools and information needed to apply the techniques to certain classes of problems, to understand the elements and parameters of significance, and to develop an understanding of the approaches which must be undertaken in certain instances in order to develop meaningful results.

The final chapter contains a bibliography which can be used to supplement the information in this volume and which can be used as a source of more detailed data with respect to each of the topics contained in the Notebook.

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* Volume 2 of the RADC Reliability Notebook contains detailed failure rate data.

CHAPTER 2

RELIABILITY CONCEPTS

1. RELIABILITY IN SYSTEM DEVELOPMENT

In recent years there has been a continuous demand for more extensive and sophisticated hardware systems to meet national defense requirements. This demand has been accompanied by advancements in analytic techniques for determining defense needs and for taking an integrated systems approach to meeting defense objectives. Advancements in these analytic techniques have shown that an integrated systems approach to hardware development and procurement is often required in order to meet performance goals within specified schedule, finance, and resource constraints. Without an integrated approach, standardization objectives may not be met; systems may be designed which require maintenance and operational talents far exceeding those required to be compatible with other system segments or performance needs; and interface problems might be created which could seriously affect the capability to fully utilize system characteristics. The realization that these and other undesirable effects could be more nearly corrected through an integrated approach to development and procurement together with the development of more sophisticated analytic techniques and the means for practically applying them has been a key force in motivating the Department of Defense and the Air Force toward a total systems approach. As one means of implementing this approach, the Air Force has developed a series of publications (e.g., the AFSCM 375-series) designed to provide the Systems Project Office (SPO), systems program managers and project engineers with guidelines, recommendations and requirements to help ensure that a systems approach is being taken during each of the development and life cycle phases and to help with the decision making and information flow processes. These publications cover a wide variety of organization, technical, procedural, reporting and data flow recommendations and requirements which system managers and project engineers are expected to follow in order to achieve procurement and performance objectives. In certain instances particular disciplines require additional emphasis because they are significant in terms of their impact on system performance. One such discipline is reliability in terms of reliability program and engineering management information and reliability engineering techniques and the significant impact these activities can have on system reliability as a performance characteristic.

In reality, reliability as a performance characteristic has been a key factor in systems and equipment development and procurement. However, demands have been oriented toward more complex versatile

systems and increasingly higher levels of reliability with each new generation of weapon or communication system. For example, during the 1950's an MTBF of 50 hours was often acceptable for a system of moderate complexity. By the early 1960's, however, this value had increased to the order of 100 to 500 hours for systems of equivalent or even higher complexity. Currently, an MTBF requirement of 1000 hours is not uncommon, and within another decade an increase to 10,000 hours or higher is conceivable. This demand for increasingly higher levels of reliability has been taking place while system functional complexity also has been increasing at a comparable rate. This continuing demand for increased reliability and system complexity has resulted in increased emphasis on reliability engineering, management, program, and analytic techniques for meeting these objectives.

One approach to meeting the requirement for increased emphasis on reliability oriented efforts is to provide guidelines and information which can be used as a basis for implementing organizational structures of which reliability is an integral part, directing reliability oriented technical efforts and analyses, and evaluating periodic and final results to ensure that reliability as well as other important technical, performance, and physical characteristics and goals have been met.

This Volume I of the RADC Reliability Notebook has been developed with that specific purpose---to provide the System Project Office (SPO) and System Program Directors with guidelines which will help ensure that reliability performance objectives for large scale complex systems will be met and to provide information which will permit application of the guidelines to smaller scale programs as well. The basic philosophy of Volume I is oriented toward application of techniques and effort required to establish meaningful reliability objectives commensurate with tactical and performance needs and to meet these objectives within resource, financial and schedule constraints. The concepts and information presented are directed toward two basic disciplines, Reliability Assurance and Reliability Achievement. Reliability assurance includes activities directed toward establishing appropriate reliability development goals, monitoring program activities, and evaluating results to verify that established goals are reached. Reliability achievement includes application of reliability engineering techniques performed for the specific purpose of achieving the required level of reliability.

2. RELIABILITY ASSURANCE

Reliability assurance, i.e., reliability program functions that are performed for the explicit purpose of assuring that a required level of reliability is achieved, is probably the most important function of the reliability group of the system program office. Reliability assurance involves a

variety of activities that can be classified under four general functions: allocation, specification, prediction and demonstration. The various reliability assurance functions typically occur during different phases of the system life cycle.

Reliability allocation is the process of establishing reliability requirements for various subdivisions of a system based on a previously established overall system reliability goal. Overall system reliability requirements typically are derived from the operational requirements and constraints of the mission. Once this level has been established, a number of interrelated factors such as importance or criticality, and complexity of individual functions are weighed against state-of-the-art limitations and various design constraints to arrive at compatible and practical levels of reliability for each defined subdivision of the system.

The second major activity of a reliability assurance program is that of developing the reliability requirements for the system and detail specifications. The general System Specification which contains the technical requirements for the system as an entity, is usually prepared by the procurement organization, and provides the basic technical requirements governing the contract definition activities. The System Specification contains reliability requirements that must be stated in quantitative terms. The preliminary reliability allocation activities provide the principle input to the development of the system reliability requirements. In fact, a reliability apportionment model supporting the allocation of reliability values assigned to system segments is recommended as a part of the reliability requirements paragraph of the System Specification.

The general reliability requirements of the System Specification are subsequently refined and expanded during the preparation of the Detail Specification. These specifications include requirements peculiar to the design, development, test, and qualification of individual contract end items, and includes specific reliability requirements stated in appropriate quantitative terms.

One major reliability oriented activity during system development is that of assuring, with an acceptable level of confidence, that the specified reliability requirements are being met before the design has progressed to the point that changes are impractical. This portion of the reliability program involves application of techniques of reliability prediction, i.e., estimating the probable level of reliability that will be achieved based on characteristics of the system design.

The results of a reliability prediction provide quantitative information concerning the probable level of achieved reliability, help to identify weak or problem areas in the design, and provide a quantitative

evaluation of proposed design changes. Another important use of reliability prediction is in performing reliability analyses for use in design reviews.

Once a design is accepted, and as end items are produced, the achieved level of reliability is demonstrated as a part of the acceptance tests. The objective of reliability demonstration is to obtain quantitative empirical evidence that the hardware is in compliance with specified reliability requirements. The demonstrations are conducted in accordance with an approved test plan which includes a statistically designed procedure specifying test duration, test conditions, sample size and acceptance criteria.

3. RELIABILITY ACHIEVEMENT TECHNIQUES

Reliability achievement includes reliability engineering and improvement activities that are performed throughout the system life cycle, and which influence system design. Several distinctive techniques or engineering methodologies include derating, redundancy, simulation, and data feedback and analysis.

Part derating is a design technique used to reduce the probability of failure of parts in a particular design. Through this technique, a safety factor is established by selecting parts capable of withstanding stresses in excess of those likely to be encountered during operation. Thus, failures that result from normal variations in operational stresses can be significantly reduced.

Redundancy is the technique of providing alternate devices or methods for performing a given function when the primary device or method has failed. In some cases a complete standby system is duplicated, while in other cases redundancy can be applied to equipments, units, or even individual parts. Judicious application of redundancy can result in very significant improvement in system reliability. However, size, weight and cost restrictions often necessitate careful trade-off analyses in optimizing the design approach.

Simulation, or artificially approximating functional characteristics, is a valuable tool which has direct application in reliability engineering. Two basic types of simulation are commonly used in system development. Computer simulation of system functions provides a method for "exercising" a design before hardware items are produced. A mathematical model, generated to describe all functions and interface relationships of the system, is programmed for solution by analog or digital computer. Appropriate variation of input data during solution provides dynamic evaluations of the system design. Such simulation

can be used to evaluate design reliability in terms of changing operational demands and in terms of total system configuration before expensive hardware items are produced.

A second type of simulation is that of exercising hardware models of system components under simulated operational conditions. A range of environmental conditions and operational stresses are artificially produced in a carefully controlled manner. Such simulation permits empirical reliability data to be generated under precisely known conditions and stresses. The data thus generated can be used as the basis for determining the source of reliability problem areas and for developing appropriate corrective measures.

Reliable systems are the result of mature designs reflecting experience gained during successive redesign and test cycles, and during the operational phases of previously developed systems. In order to take full advantage of such experience, it is essential that all pertinent historical data be available to the design engineer. Therefore, an important activity of reliability achievement is the acquisition of test and operational data, the analysis of these data to extract pertinent reliability information, and the presentation of such information to design engineering groups in a useful form. As a result of the need for effective data feedback and analysis procedures to support reliability improvement programs, efficient and uniform data collection and analysis procedures have been developed and are available to the reliability engineer. These procedures are proving to be one of the basic tools of reliability improvement activities.

4. RELIABILITY MANAGEMENT AND ENGINEERING

There are two general types of effort which make use of reliability assurance and achievement disciplines. These are reliability program management effort and reliability engineering effort. The management effort is oriented toward establishing responsibilities, planning, and creating organizational relationships and toward determining basic approaches for implementing pertinent organizational and engineering activity which can be effective in monitoring reliability performance, encouraging application of reliability engineering techniques, and evaluating results. The reliability engineering effort is oriented toward application of specific reliability engineering techniques, approaches and data under various design, chedule and development conditions.

Thus management effort is very directly related to assurance activities and engineering effort is directly related to achievement activities though there is some overlapping which may vary from phase to phase.

Considering lead times, degree of coordination required in the development of complex systems, and the increasing importance of reliability as a major objective of system design, it is essential that reliability efforts be integrated into the overall system development program during all phases of the system life cycle. Specific activities that are effective in ensuring that appropriate reliability goals are established and met vary from phase to phase. Program management effort that is effective in assuring reliability during early phases is quite different from the kind of effort that may be required in later phases. Reliability engineering techniques that are most appropriate also depend on the particular life cycle phase. Therefore an effective reliability program should include provisions for an appropriate organization and the coordination of activities to provide a continuous program that progresses from phase to phase as a part of the overall system development program.

The techniques and guidelines presented in this notebook are related, where possible and appropriate, to life cycle phases of system development.

5. RELIABILITY PROGRAM ACTIVITIES

Ultimate responsibility in system reliability rests with the System Program Director, who has the responsibility to see that the reliability program requirements, organizational elements, and resources have been appropriately established and to ensure that effective reliability assurance and achievement activities are performed and verified at each significant program milestone.

Typical reliability management and reliability engineering assurance and achievement activities during the Conceptual, Definition, Acquisition and Operational phases of a system life cycle are summarized below. These are discussed in more detail in subsequent chapters of this notebook.

5.1 Reliability Program Activities During the Conceptual Phase

The conceptual phase is the earliest defined phase of the system life cycle. During this phase, when system concepts are being established, the role of the reliability program is not always clearly defined. The important activities revolve around interpreting system operational objectives in terms of reliability requirements, and performing initial allocation analysis to define reliability goals for individual subsystems.

The objective of the reliability program effort during the conceptual phase is to assure that appropriate and realistic system and

subsystem reliability requirements are incorporated in the Preliminary Technical Development Plan (PTDP) which is the basic document governing the Definition Phase activities.

5.2 Reliability Program Activities During the Definition Phase

The Definition Phase of the system life cycle is devoted to translating system functional requirements generated during the conceptual phase into detailed system and system element requirements that will govern subsequent acquisition efforts. During this phase, the reliability program includes both assurance and achievement activities. Reliability assurance activities include refinement of system reliability allocations to provide meaningful reliability requirements for the initial system specification, and review and evaluation of competing contractor's proposals to assure that the reliability requirements will be met. Reliability achievement or engineering activities during this phase include modeling, predictions and trade-off study analyses in expanding system specifications, and developing basic design approaches to be included in Acquisition Phase proposals.

5.3 Reliability Program Activities During the Acquisition Phase

The Acquisiton Phase is devoted to development, production, and government acceptance of items on contract. During this phase, a variety of reliability assurance and achievement activities are performed. Some of the more important reliability achievement activities during the acquisition phase include consideration of reliability objectives and constraints in performing design trade-off analyses, ensuring application of effective reliability engineering principles in the design, (selection of reliable parts, derated part applications, redundant configurations and other reliability design/engineering techniques) and implementing design changes where necessary to improve reliability. These activities are supplemented by reliability assurance functions such as imposing reliability requirements on subcontractors and vendors, and developing and implementing reliability evaluation and test programs to assess the reliability of the final product.

5.4 Reliability Program Activities During the Operational Phase

The Operational Phase begins when the first contract end item is accepted and turned over to the user, and continues until disposition of the system. The reliability program during this phase includes reliability achievement activities such as engineering analyses and development of reliability improvement modifications. Other key reliability activities during the Operational Phase include collection

and analysis of field failure data, including data from reliability demonstrations performed during operation testing, and assuring that modifications introduced for reasons other than reliability do not degrade system reliability.

6. RELIABILITY PROGRAM INFORMATION

The preceding discussion serves as an introduction to the need for and major objective of the reliability program during the system development cycle, and has identified certain fundamental reliability achievement and assurance activities. This chapter has been presented to establish a point of reference and departure for the balance of the handbook which contains detailed discussion of the various reliability concepts and program activities identified herein. A more comprehensive overview of the total reliability program can be obtained by reviewing the introductory paragraphs of each of the succeeding chapters.

Additional general information concerning various aspects of reliability programs can be found in current literature such as the military documents listed below. Additional references on specific subjects are presented at the end of each chapter where appropriate, and a complete bibliography is presented in Chapter 12.

<u>Reliability Management Handbook</u>, Arinc Research Inc. Report No. TOR-269 (4303)-9, 14 February 1964. (DDC No. AD 463303 and AD 463304). This report describes the reliability program management activities of the SPO as related to the Space Systems Division, AFSC; and responds to the requirements of MIL-R-27542A(USAF), "Reliability Program Requirements for Systems, Subsystems and Equipments." It does not contain discussions of reliability engineering techniques and procedures.

<u>Handbook of Reliability Engineering</u>. NAVWEPS 00-65-502, 1 June 1964. This handbook presents reliability methods for application by project management and engineering personnel within the Bureau of Naval Weapons. This handbook is primarily concerned with engineering practices and methods, however, and presents management concepts in a cursory manner.

<u>Reliability and Maintainability Program for Material</u>. Combat Operations Research Group Memorandum CORG-M-181, 1 August 1964. (DDC No. AD474356). This document presents the results of a study to define the reliability/maintainability program of the U. S. Army Combat Development Command, based on interpretation of AR 705-25 and AR 705-26. This provides interpretations of Department of the Army policy, and should be used with care in connection with Air Force programs.

Reliability Design Handbook, NAVSHIPS 94501. This handbook describes reliability design techniques and procedures and includes discussions of various aspects of the reliability programs of the U. S. Navy Ships Systems Command. This handbook provides a brief discussion of certain management considerations, but is primarily engineering design oriented. The specific activities of system life cycle phases are not defined.

CHAPTER 3

RELIABILITY PROGRAM MANAGEMENT

1. INTRODUCTION

In view of the critical need for effective system management during the entire life cycle of the system, the Air Force System Command has instituted a System Program Management Procedure which is described in detail in manual AFSCM 375-4. This document provides direction and guidance for management of a phased program as applicable to the conception, definition, acquisition and operation of large-scale systems. However, the basic concepts of AFSCM 375-4 are also applicable to many non-system programs with management requirements similar to those of major system programs. Many of the program functions also are applicable to procurement activities, even though specific life cycle phases may not be defined.

Throughout the system life cycle, many managerial and technical disciplines are applied to assure a suitable system within constraints of various parameters such as cost and time. Reliability management and engineering activities included throughout the system life cycle are included among the more significant of these disciplines.

Many program functions defined in AFSCM 375-4 require data resulting from specific activities of a reliability program. However, with few exceptions, these activities are not specifically defined in relation to reliability program requirements. The objective of this chapter is to identify specific system program management actions involving or related to reliability program activities, to briefly describe these activities and indicate their relationship to the overall system program management structure.

2. OBJECTIVES OF RELIABILITY PROGRAM MANAGEMENT

The final objective of system program management is the timely delivery of systems meeting defined operational requirements within the constraints of available resources. In support of this, the final objective of a reliability program is to assure delivery of systems that meet specified reliability requirements.

A group of specific objectives of reliability program management can be defined which, if achieved, will help to assure that the final objective is reached. These specific objectives are:

a. Provide the framework for assuring appropriate consideration of reliability requirements in establishing functional and physical configuration of the system.

b. Insure an effective reliability program during system definition, acquisition and operation.

c. Balance reliability factors against other factors such as performance, time and cost to obtain the required system.

d. Minimize the technical, economical and schedule risks in assuring reliability achievements and verification during the development and production effort.

e. Control reliability aspects of changes in system requirements during development and production. This includes changes performed to achieve a specified level of reliability, as well as those that are performed for other purposes, but which may impact on reliability.

f. Establish a high probability of success in obtaining a reliable system in a timely, economical manner.

g. Document decisions concerning, and impacting on the reliability program.

h. Establish a discipline for the reliability elements of a System Program Office (SPO) to follow so that a closed-loop effort is maintained between the reliability activities and other associated activities such as maintainability, safety, and human factors; and with the functional areas of procurement and production, program control, configuration management, system engineering, test and deployment, and logistics.

i. Manage and control the reliability program efforts of contractors. Identify significant reliability program functions to be performed by other organizations such as Air Force Logistic Command (AFLC) and using commands participating in systems management.

j. Establish requirements for flow of reliability and related information between responsible organizations.

k. Accomplish or manage the accomplishment of reliabilty program actions as identified for the definition, acquisition and operational processes.

3. RELIABILITY PROGRAM MANAGEMENT ACTIVITIES

Reliability program management activities throughout the system life cycle are discussed in the following paragraphs. These are presented as a general discussion representing a "typical" system development program, and follow the concepts of the system program management

procedures presented in AFSCM 375-4. Actual reliability program management activities performed in support of a particular system development program could vary somewhat depending on the specific program requirements and the type of system involved. However, the fundamentals presented here are applicable to any program. Key reliability program activities that are applicable even in the case of small-scale development or procurement programs where identified phases of a system development program are difficult or impossible to define, are emphasized in the respective discussions.

The system life cycle phases, as defined in AFSCM 375-4, and the fundamental purpose of each of the phases are as follows:

<u>Conceptual Phase</u>: Develop requirements and concepts for Air Force systems which will fulfill military defense objectives.

<u>Definition Phase</u>: Sufficiently define the cost, schedule, and system elements required to satisfy the requirements developed during the Conceptual Phase.

<u>Acquisiton Phase</u>: Acquire and test the system elements as defined.

<u>Operational Phase</u>: Provide the using command or organization with the system elements and the logistics and engineering support required to accomplish the mission of the system.

4. RELIABILITY PROGRAM MANAGEMENT DURING THE CONCEPTUAL PHASE

Reliability program management activities performed during the Conceptual Phase should be directed toward establishing appropriate and feasible system reliability objectives or goals. During early stages of this phase, the foundation is established for specific reliability program activities that become evident later in the phase. Usually, the first input identifiable as specific activities of the reliability program are those concerned with the quantification of reliability requirements in preparation for the initiation of the Definition Phase. However, these requirements are based on the results of earlier activities during system planning studies or exploratory and advanced development. Therefore, early Conceptual Phase activities are summarized here in relation to their impact on later reliability program activities.

4.1 Early Conceptual Phase Activities

The Conceptual Phase includes activities directed toward identification and formulation of system requirements, development of the system concept (system planning), and development of new technology. These three areas of activity progress concurrently toward the Conceptual Transition activities that terminate the Conceptual Phase and initiate the Definition Phase.

The first specific requirements for an identifiable system are formulated by a Using Command and are documented in a Qualitative Operational Requirement (QOR). This document describes the requirement for an operational capability, describes the threat environment, and postulates an operational concept, and contains much of the mission-oriented information that will be used later in establishing system reliability goals.

The first major involvement of AFSC in system development is the long-range system planning centered about the AFSC Technological War Plan (TWP). This plan responds to the QOR, and defines environmental, technological, and resource requirements of the proposed system. Therefore, some of the important constraints that will be imposed on the reliability development activities are identified in the TWP.

Where the need is evident, the TWP initiates Systems Planning Studies which consider qualitative factors relating to operational and technical capability, together with the defined operational requirements factors in more completely defining the requirements of the system. Thus, the System Planning Studies provide information directly related to subsequent development of system reliability objectives.

The other area of activity, technological development, includes the exploratory and advanced development activities that are based on findings of previous research programs as well as on identified system requirements. In many cases, advances in reliability technology are obtained as a direct or indirect result of research, and it is essential that such knowledge be included in the reliability aspects of system development activities.

Technological development activities, identifiable as Exploratory and Advanced Development, are directed toward specific military problem areas, and development of advanced technological concepts that are directly applicable to specific systems. Such development efforts normally involve investigation and development of operational or performance concepts. However, it is possible for a stated level of achieved reliability to be a primary development objective. In any case, the results of these development activities of the early Conceptual Phase should be given careful consideration in establishing the reliability goals for the system, and in developing the approach for meeting these goals.

4.2 Reliability Program Activities During Conceptual Transition

Following the successful completion of the early system requirement, system planning and technological development activities.

and upon receipt of a Specific Operation Requirement (SOR), Operational Support Requirement (OSR), or specified Advanced Development Objective (ADO), a series of Conceptual Transition activities are performed to prepare for the initiation of the Definition Phase. Typically, the System Program Office cadre is established at this time and the first actions clearly identifiable as Reliability Program activities are initiated.

The most significant efforts during Conceptual Transition are the System Engineering activities whereby operational requirements are translated into system performance requirements. It is during this effort that requirements for system effectiveness are first interpreted in terms of reliability, human performance, safety and maintainability. The results of the Conceptual Transition engineering effort provide a significant input to the Preliminary Technical Development Plan which, together with the Program Change Proposal (PCP), the Military Construction Program (MCP), and the Secretary of the Air Force's Determinations and Findings (D&F) forms the Program Requirements Baseline, which governs the activities of the Definition Phase.

The reliability program management efforts during Conceptual Transition should be directed toward assuring the accomplishment of a variety of related activities such as those described below. (Each of these areas of activity are discussed more thoroughly in the chapters referenced in parentheses.)

a. Reviewing previous documents to identify all factors pertinent to the reliability program, and maintaining an updated listing of all such documentation. (Chapter 4)

b. Quantifying the gross level of reliability which must be met to satisfy system requirements. (Chapters 4 and 6)

c. Developing reliability block diagrams reflecting the functional relationships of the system. (Chapters 8, 9, and 11)

d. Identifying system functions of particular importance to the reliability development effort. This includes functions defining operating periods, cycles, or major mission segments on which reliability requirements are to be based, and additional functions defining the constraints affecting reliability achievements. (Chapters 4, 6, 8, and 11)

e. Performing basic reliability allocation studies. (Chapter 8)

f. Preparing the reliability program requirements input for the initial PTDP. This includes development of such factors as:

- Reliability apportionment, prediction, and modeling. (Chapters 8 and 9)

- Expected environmental conditions. (Chapter 11)

- Requirements for reliability participation in Design Reviews. (Chapters 4 and 6)

- Requirements for reliability tests, demonstration and resolution of problem areas. (Chapters 6 and 10)

4.3 Initial Reliability Program Activities in Non-System Procurements

During the early stages of non-system programs for the procurement of individual equipment items, experimental models, commercial items, and similar procurements, a conceptual phase, as such is seldom defined. However, certain reliability program activities are necessary for most programs such as those starting at the time that the operational requirements and design goals are being defined, and continuing throughout the design and production stages of the procurement program. The earliest of these activities would be performed at a time during the equipment development cycle that was equivalent to the conceptual phase of the system life cycle.

In certain programs, such as in the development and procurement of large equipments for the normal inventory, all reliability program activities indicated in paragraph 4.2 may be necessary. In other cases, the reliability program should be scaled down to be commensurate with technical and economical constraints of the particular procurement. As a minimum, however, the reliability program should include the activities necessary for reviewing related documentation, developing gross reliability requirements, and defining the reliability program activities to be performed during design and production. (See items a, b and f of paragraph 4.2. Also see paragraph 5 of Chapter 5.)

5. RELIABILITY PROGRAM MANAGEMENT DURING THE DEFINITION PHASE

In general, the Definition Phase is divided into three subphases as follows:

<u>Phase A</u> includes the activities necessary to establish the formal SPO and prepare for contractor definition.

Phase B includes the efforts of competing contractors in performing the definition tasks, and in preparing their proposals.

Phase C includes the Air Force efforts in evaluating proposals and selecting the development contractor.

Reliability program management activities performed during the Definition Phase should be directed toward defining the cost, schedule, and technical design approach to satisfy the system reliability requirements. In general, these activities will include efforts such as preparation of reliability requirements for the system specification, preparation of reliability program plans, determining realistic cost and schedule estimates for reliability engineering in relation to other engineering, logistic production and support cost, and identifying high risk areas. In addition, the system reliability program is interpreted in terms of subsystem factors, firm and achievable reliability requirements are allocated to subsystems and reliability requirements are evaluated with reference to contracting for the system development activities of the Acquisition Phase.

Reliability program activities performed during the Definition Phase of a typical system development program are described below. In addition, sequential diagrams of reliability program activities during Phase A and Phase B are shown in Figures 3-1 and 3-2, respectively.

The discussion of reliability program activities during the Definition Phase is presented with reference to a system development program. However, many of the activities discussed in paragraph 5.1 through 5.3 below are also applicable to non-system programs. This is especially true during the normal procurement of new equipment items for the operational inventory when the development program includes activities equivalent to the Definition Phase of a system development program. Those activities that will be most important to a program of this type are:

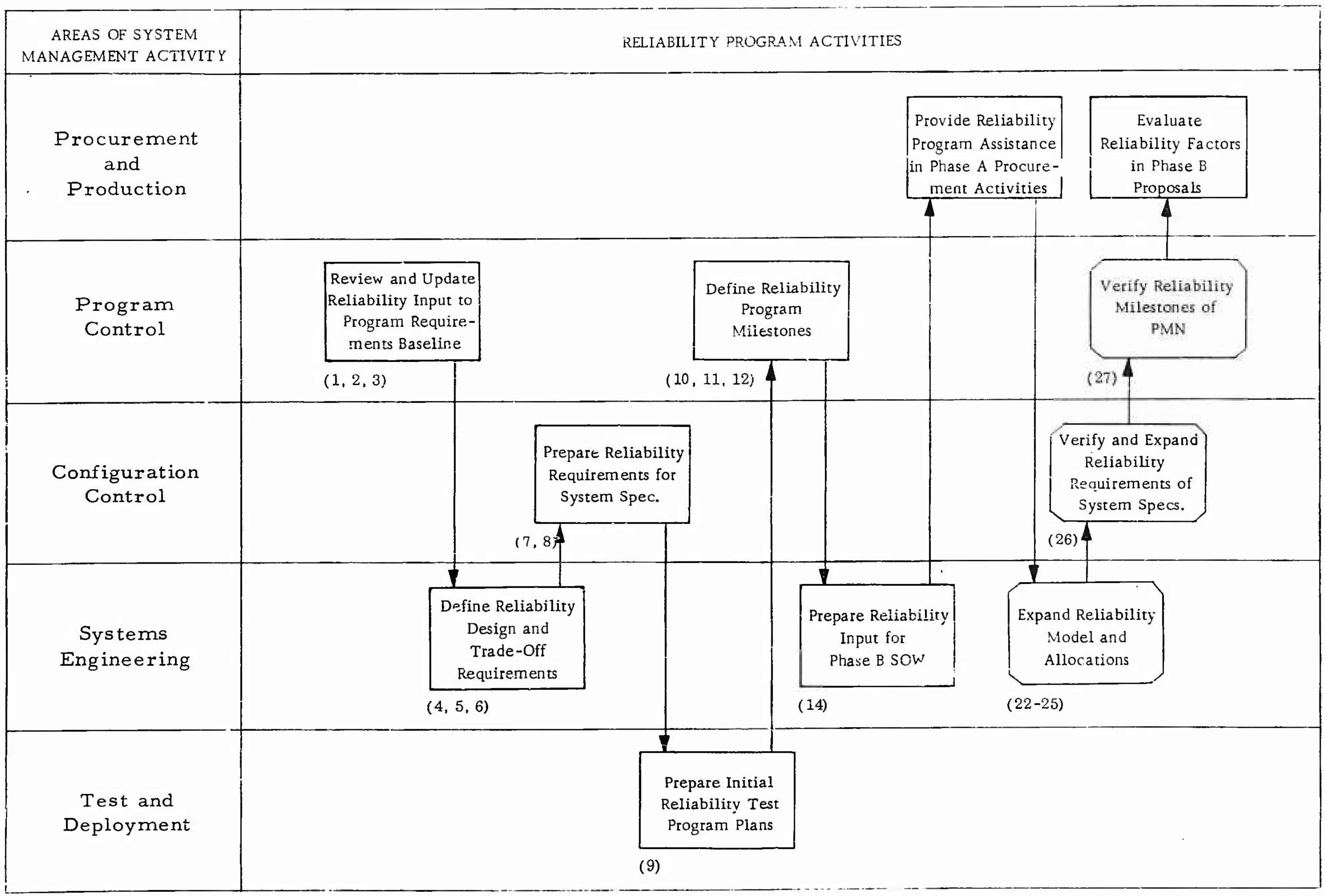
- Preparing reliability input for contractor definition SOW. (See paragraph 5.1 f.)
- Evaluating reliability factors in contractor definition proposals. (See paragraph 5.1 i.)
- Preparing reliability requirements input for CEI Detail Specifications. (See paragraph 5.2 d.)
- Preparing Initial Reliability Test Plans. (See paragraph 5.2 e.)
- Evaluating contractors proposals for development. (See paragraph 5.3.)

5.1 Reliability Program Activities During Phase A

Following the receipt of the System Definition Directive (SDD), SPO cadre is augmented to create the formal System Program Office (SPO) under the direction of the System Program Director. The SPO is composed of two divisions performing the staff functions of Program Control and Configuration Management, and three line divisions headed by the Deputy Director for Procurement and Production, the Deputy Director for Engineering, and the Deputy Director for Test and Deployment.

The responsibility for reliability engineering during Phase A is delegated to the Deputy Director for Engineering who assigns reliability specialists to emphasize the reliability discipline as an integral part of the total system engineering process. In addition to reliability engineering activities, however, the reliability program also supports the program control, configuration control, procurement, and test activites of the other divisions. This wide range of program support activities during Phase A is illustrated in Figure 3-1. The reliability program activity blocks in this diagram are shown in rows corresponding to the most closely associated area of system management. In addition, each block of Figure 3-1 is keyed to one or more blocks of Figure 6 of AFSCM 375-4. The reliability program activities are typically performed in the sequence as indicated by the diagram. However, in a particular program, the sequence of activities may vary, or several activities may be combined or performed concurrently. The reliability program activities indicated by each block are described more fully in the following discussions which are identified according to the respective block of Figure 3-1. The numbers in parentheses following the subject headings refer to blocks in Figure 6 of AFSCM 375-4.

a. Review and Update Reliability Input to Program Requirements Baseline (1, 2 and 3). One of the initial activities of the SPO is the review and revision of the PTDP with respect to other requirements of the System Definition Direction. At this time, control of technical inputs to the Program Requirement Baseline (i.e., the performance requirements, design criteria, and other data defining the technical requirements of the system) is assumed by the Configuration Management Division. Direct support is provided by the Deputy Director for Engineering, who is responsible for the development, integration, interface compatability, and validity of the reliability input. Thus, the earliest activities of the reliability specialists should include reviewing the reliability and related requirements and developing recommended changes to the PTDP. Typically, such recommendations would be approved by the Deputy Director for Engineering before submission to the Configuration Management



NOTES: Numbers in parentheses relate to block numbers in Figure 6 of AFSCM 375-4.

[rectangle] = Air Force Activities　　[rounded box] = Contractor Activities

Figure 3-1. Reliability Program Activities During Phase A

Division for final approval. The approved change is then incorporated in the PTDP by the SPO Program Control Division.

b. Define Reliability Design and Trade-Off Study Requirements (4, 5 and 6). The reliability engineering process started during Conceptual Transition is continued as the first major reliability engineering efforts of the Definition Phase. The system reliability requirements are expanded to establish a basis for allocation of various requirements among the system elements and defining subsystem reliability requirements as required for preparing the initial System Specification. (See Chapter 8 for discussion of Reliability Allocation Procedures.)

In the process of determining system performance and design requirements, and during the process of defining the various requirements and constraints such as safety, reliability, and maintainability, many alternative methods will be identified, the most fruitful of which should be selected for input to trade-off studies. At this time, the reliability considerations should be examined from a total systems point of view to identify subsequent trade-off study considerations. An important function of system reliability engineering at this time is that of assuring that reliability will be given its appropriate weight and that essential constraints are established such that the achievable level of system reliability is not degraded beyond acceptable limits. Trade-off studies involve the application of many disciplines as discussed in this notebook. The effect of trade-offs on system reliability are usually evaluated using reliability prediction procedures as described in Chapter 9.

c. Prepare Reliability Requirements for System Specification (7 and 8). The first major configuration control activity following the assumption of technical control of the baseline documents by the SPO, is that of preparing the initial System Specification to be included in the Phase B statement of work.

The management control of the System Specification is the responsibility of the Configuation Management Division. However, all technical input, including the reliability requirements are the responsibility of the Deputy Director for Engineering.

The System Specification includes a paragraph that specifies the system reliability requirements in quantitative terms. In addition, the System Specification states system reliability acceptance testing requirements (see Exhibit I of AFSCM 375-1). Development of these requirements should be the

direct responsibility of the reliability spe ialist, who should be supported by the Test and Deployment Division in the development of reliability test requirements.

Techniques used in the development of reliability requirements are discussed in the reliability specification portion of Chapter 6.

d. Prepare Initial Test Program Plans (9). The Deputy Director for Test and Deployment is responsible for initiating the development of plans for the su quent testing of the system. These are essentially management-oriented planning documents to guide the accomplishment of the overall system test program, assure adequate lead time for development of test procedures and facilities, and provide a basis for more detailed planning and operating documents. Any requirements for extensive and time consuming reliability testing are important inputs in the development of these plans, and identification of any such requirements should be initiated at this time. Therefore, reciprocal support will be essential between the reliability and test specialists in developing reliability test requirements for the System Specifications, and in preparing initial reliability test program plans.

Some of the factors to be considered in the development of reliability test program plans are discussed in Chapter 6. Also details of the development of reliability test procedures are presented in Chapter 10.

e. Define Reliability Program Milestone (10, 11 and 12). The first major activity of the Program Control Division of the SPO, following the verification of the Program Requirements Baseline, is that of developing the preliminary Program Work Breakdown Structure (PBS) and Program Management Network (PMN). This function is primarily system program management oriented, but is influenced by systems engineering and other groups to the extent necessary for assuring the definition of all critical milestones of the network. In particular, the system reliability management inputs should include requirements and schedules for development of reliability program plans, reliability design reviews, reliability test plans, and other reliability milestones of the overall PMN.

Specific activities and milestones of the reliability program are summarized in this chapter. In addition, the reliability engineering management activities, and reliability data management considerations as discussed in Chapters 4 and 5, respectively, will aid in identifying the reliability program

activities, and establishing associated milestones for the Program Management Network.

f. Prepare Reliability Input for Phase B Statement of Work (14). The Deputy Director for Engineering is responsible for preparation of the Statement of Work (SOW) for the Phase B effort. The most significant portion of the Phase B SOW, insofar as reliability program management is concerned, is the statement of Phase B system engineering effort, which includes requirements for trade-off studies involving system reliability as one of the principal parameters of system effectiveness. Also, specific reliability requirements should be stated in the requirements for preparing the Part I Detail Specifications for each CEI, and in updating the System Specification.

Other portions of the SOW that include, or are impacted by reliability considerations are the requirements for system reliability evaluation in design reviews, and the requirements for development of reliability program management plans.

The reliability specialist should also review documents referred in the SOW to assure that appropirate reliability specifications are imposed, that only essential reliability requirements are listed as applicable, and that duplicate or contradictory requirements are not generated by secondary reference. It is the reliability specialist's responsibility to determine the reliability data items to be specified in the Contract Data Requirements List, DD form 1423. See Chapter 5 for guidance in establishing reliability program data requirements.

g. Providing Reliability Program Assistance in Phase A Procurement Activities (19 and 21). A series of procurement and production management actions are performed to complete the request for proposals (RFP), and solicit bids for performing Phase B. These actions involve activities of all participants, including the reliability specialists from the office of the Deputy Director for Engineering. Some of the more significant activities of the reliability specialists during the final procurement actions include:

- Updating the reliability inputs to the Phase B SOW.

- Performing final review and verification of the reliability requirements in the intial System Specification.

- Reviewing and updating as necessary the system reliability test plan.

- Developing criteria for evaluating the reliability factors in proposals.

- Review information relating to any reliability achievement incentive provisions in the RFP.

- Providing consultation or direct assistance to the Source Selection Advisory Council (SSAC) in rating reliability provisions in contractors' proposals.

- Providing assistance to pre-proposal briefings where questions may be asked concerning technical aspects of the reliability program.

h. Contractor Reliability Program Efforts in Proposal Preparation (22 through 27). Contractors selected to submit proposals will typically perform a series of iterative actions that culminate with a definitive proposal for performing Phase B. One of the major activities in proposal preparations is in performing selected studies and identifying additional trade-off study requirements for Phase B. One of the major efforts in the support of such trade-off studies will be the expansion of the reliability model, and refinement of the reliability allocations to reflect the contractor's proposed system design characteristics.

The contractors' proposal development should also include updating and verifying the reliability requirements provisions in the System Specification.

Ideally, each contractor will review, verify and expand the reliability requirements paragraph of the System Specification based on the expanded reliability model and refined reliability allocations to provide reliability requirements for identifiable system elements. Additional activities performed by the contractor should include verifying and expanding the reliability program activities and milestones of the PMN.

i. Evaluate Reliability Factors in Phase B Proposals (33). Proposals received from the several contractors in response to the Phase B RFP are evaluated using previously established evaluation criteria. Each technical and managerial factor of the proposal is scored according to an objective scoring system, and the contract is awarded accordingly.

The SPO reliability program should include provisions for evaluating the reliability aspects of the proposals. The weight

accorded reliability factors during the proposal evaluation will vary depending on the requirements of the system under development. This weight may or may not constitute a significant portion of the total score. However, regardless of the relative weights established for the reliability factors, failure to meet the minimum reliability requirements can be grounds for rejecting the proposal, even though all other factors meet the SOW requirements.

5.2 Reliability Program Activities During Phase B

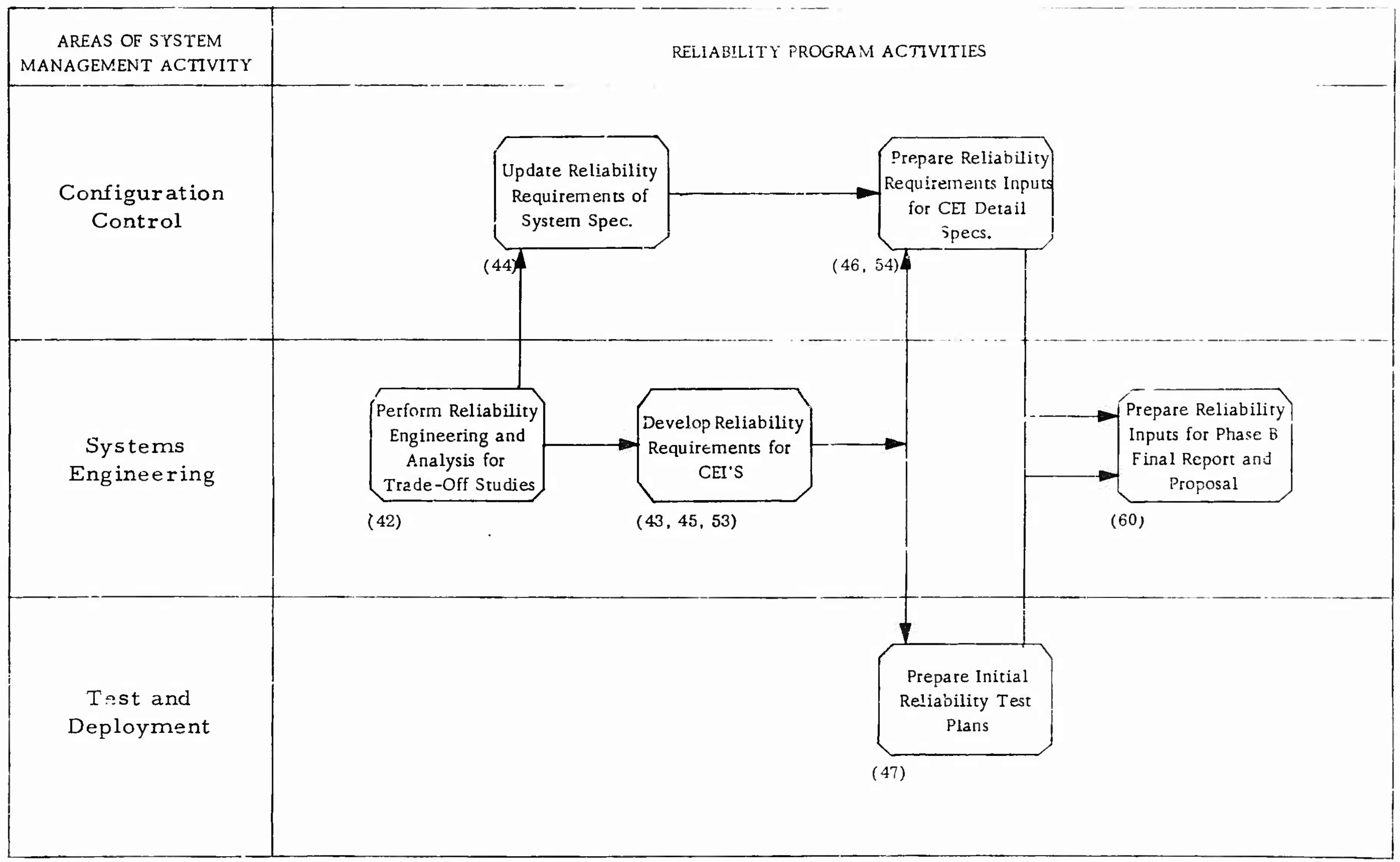
Following final review, the Phase B contracts are signed and distributed to the contractors to officially initiate Phase B. From this point until the completion of Phase B the SPO will fully support and coordinate the contractor effect. The contractor's activites during Phase B represent an iteration in depth of the preceding activities, including the preparation of the complete System Specification, and preparation of detailed plans and schedules for system development. Figure 3-2 indicates the areas in which the contractor should provide for significant reliability program activites in a typical system definition program, and to which the SPO should give particular attention in monitoring and coordinating the contractors reliability program activities.

The activity blocks in this diagram are shown in three rows to indicate the SPO management areas most directly associated with the respective reliability program activities performed by the contractor. In addition, each block of Figure 3-2 is keyed to one or more blocks of Figure 6 of AFSCM 375-4.

The contractor's reliability program typically includes those activities indicated in the diagram. However, since each contractor will organize his reliability program to conform to his overall management structure, the sequence of activities, and even the relative emphasis placed on each of the various activities will vary from contractor to contractor.

The reliability program activities indicated in Figure 3-2 are discussed more fully in the following paragraphs. The numbers in parentheses following the subject headings refer to the blocks in Figure 6 of AFSCM 375-4.

a. Perform Reliability Engineering and Analysis for Trade-off Studies (42). A major effort of Phase B is the performance of trade-off studies to assure the best possible balance among total cost, schedules and operational effectiveness factors. The effect of reliability factors should be considered during



NOTE: Numbers in parentheses relate to block numbers in Figure 6 of AFSCM 375-4.

Figure 3-2. Contractor Reliability Program Activities During Phase B

all trade-off studies, not only in relation to system effectiveness achievement, but also in relation to other, often more obscure factors such as maintenance support cost. For example, logistics factors such as maintenance spare provisioning plans are directly influenced by component failure rate.

Typical reliability engineering and analysis activites associated with virtually all trade-off studies include such diversified tasks as:

- Updating the system reliability model to assess the reliability characteristics of alternative design approaches.
- Providing failure rate prediction data for alternate approaches for application to studies such as logistics cost vs. initial costs.
- Evaluating historical reliability data as applicable for activities such as assessing current equipment in the DOD inventory in selecting alternate CEI's.

b. Update Reliability Requirements of System Specifications (44). The results of the contractors system engineering and trade-off study effort are used to update and refine the System Specification. During this updating, particular attention is paid to the reliability provisions, where a valid allocation of reliability requirements to the subsystems is a prerequisite to the subsequent development of Part I Detail Specifications for the contract end items program. Therefore, the contractor's configuration control program should be fully supported by reliability engineering in assuring that system reliability requirements are properly specified.

c. Develop Reliability Requirements for CEI's (43, 45 and 53). The most significant activities performed by the contractor during Phase B are the engineering and analysis activities required to convert the gross system requirements into detailed design requirements for individual CEI's. This includes the development of all design requirements, including reliability requirements.

The following are some of the more important reliability engineering activities associated with updating the reliability requirements of the System Specification:

- Reviewing updated baseline data, such as the PTDP and System Specification to ensure complete understanding of gross system reliability requirements and constraints.

. Updating the system reliability model to reflect the system configuration, to the level of identified CEI's.

. Reviewing and updating reliability allocations to develop specific allocations of system reliability to definable CEI's.

. Establishing quantified reliability requirements for the system, subsystems, and definable CEI's and assuring the validity and practicality of these requirements.

. Establishing system reliability testing requirements compatible with the quantified reliability requirements, and applicable to the subsequent preparation of reliability test plans.

d. Prepare Reliability Requirements Inputs for CEI Detail Specifications (46 and 54). Based on the contractor's development of CEI design requirements, the Part I Detail Specifications are prepared in preliminary form for each identifiable CEI. This includes the preparation of the requirements and test sections (sections 3 and 4)of the specifications, and reflects the information in the updated System Specification and integrated system test requirements. These specifications include quantified reliability requirements for each CEI. Therefore, in preparing the reliability requirements, close cooperation will be required between system engineering and configuration control activities to assure that all reliability requirments and test provisions are carefully prepared and adequate. Some of the more important reliability engineering activities that should be performed in preparing the reliability inputs for the Part I Detail Specifications include:

. Reviewing the System Specification reliabilty allocations with respect to proposed CEI characteristics to verify the validity and practicality of each CEI reliability requirement.

. Establishing and verifying quantified reliability requirements for inclusion in the Part I Detail Specifications.

. Establishing CEI reliability testing requirements compatible with the quantified reliability requirements, and applicable to preparation of category I test plans.

e. Prepare Initial Reliability Test Plans (47). The initial test plans are refined and updated by the contractor in the preparation of initial category I test plans and inputs for subsequent category II test plans. Included in these plans are tests required to demonstrate reli ility achievement for the CEI's during category I testing, and for the integrated system during category II testing.

f. Prepare Reliability Inputs for Phase B Final Report (60). (See also paragraph 31 of AFSCM 375-4.) Phase B of the Definition Phase is concluded with the contractor's submission of his Final Report. This report, which includes the contractor's firm proposal for development, requires reliability program inputs in several areas, including:

- Reliability aspects of trade-off conclusions.
- Reliability inputs to system engineering documentation developed during Phase B. (See Chapter 5.)
- Reliability requirements in System Specifications and CEI Part I Detail Specifications.
- Reliability data requirements list for the development program of the Acquisition Phase. (See Chapter 5.)
- The contractor's reliability program management plan.
- Identification of reliability program high risk areas.
- Identification of reliability problems that could not be resolved during the Definition Phase.
- Reliability program activities that will require long lead times.

5.3 Reliability Program Activities During Phase C

The objective of Phase C is to select the definition contractor who is to continue the development program of the Acquisition Phase. Therefore, the primary activity during Phase C is the evaluation of the Phase B Final Reports, which contain the contractor's firm proposals for development, and the selection of the particular contractor for the Acquisition Phase development effort.

The evaluation of the contractor's final report typically requires a technical evaluation of the contractor's design. Such evaluation

should include a reliability engineering analysis of the contractor's design approaches for meeting the system and CEI reliability requirements, and, as such, would involve system reliability modeling, allocation and prediction activities. Thus, reliability analysis and evaluation support will be essential in evaluating the Phase B Final Reports and proposals.

After being updated as required to reflect any negotiated changes, the selected contractor's Phase B final report is used to update and refine the baseline documents that will govern the Acquisition Phase development effort. Two baselines are established as follows:

- Design Requirements Baseline, which governs the configuration management of the system development. This is based on the Part I Detail Specifications, and defines all design requirements, including system and subsystem reliability requirements.

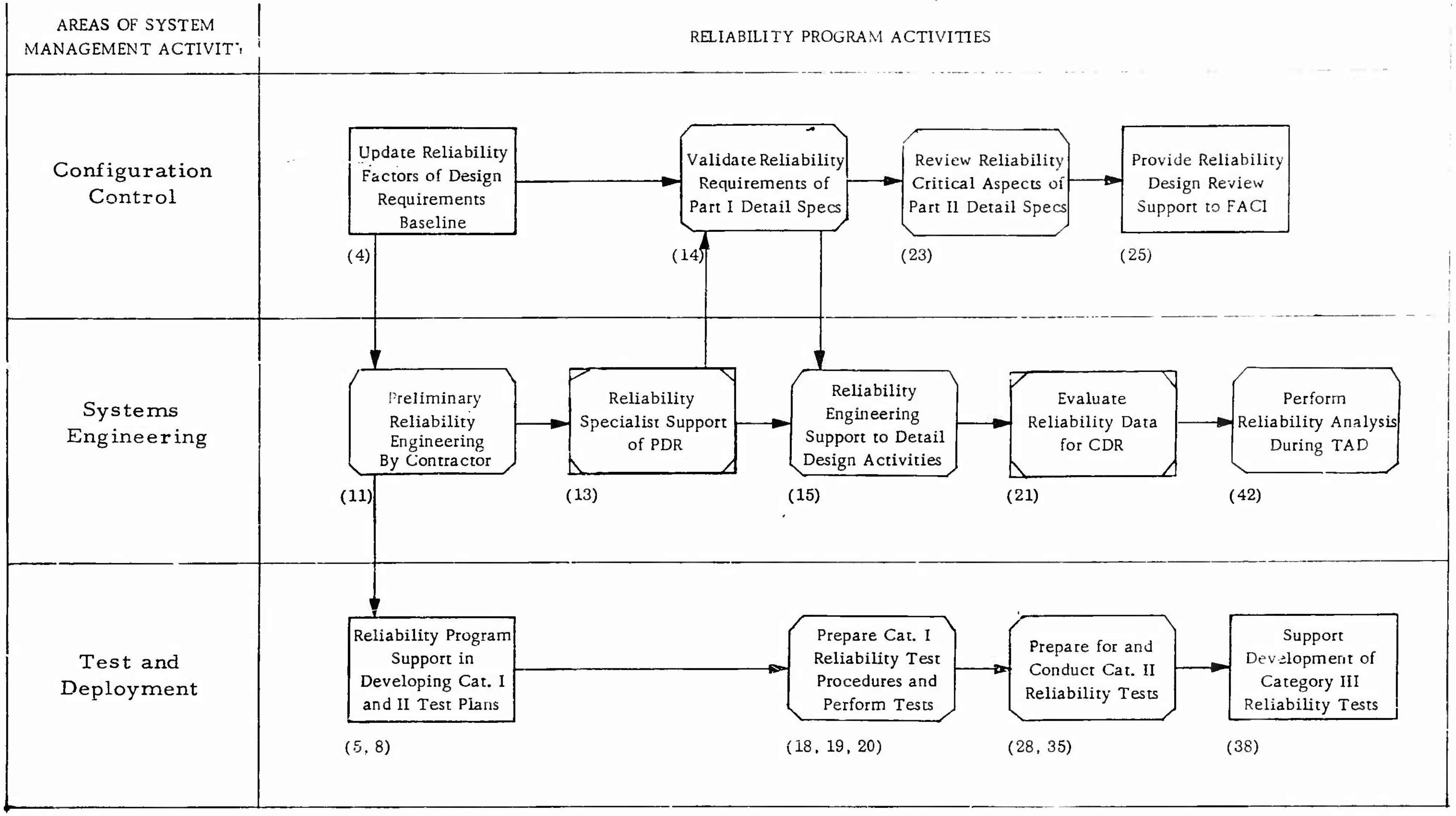
- Program Requirements Baseline, which governs the program management efforts of the acquisition phase. The previous baseline documentation is consolidated to provide the Proposed System Packaging Plan (PSPP) which includes recommendations for full-scale development.

The Definition Phase is completed, and the Acquisition Phase initiated with the issue of the System Program Directive (SPD) by Hq. USAF, which documents official approval of the design and program requirement baselines.

6. RELIABILITY PROGRAM MANAGEMENT DURING THE ACQUISITION PHASE

Reliability program management activities performed during the Acquisition Phase should be directed toward assuring that system elements as acquired meet the reliability requirements of the System Specification. In general, these activities will include contractor efforts such as detailed reliability engineering activities, updating reliability factor input for design reviews, planning and performing reliability demonstration tests as part of categories I and II testing, and providing reliability program guidance for transition to the Operational Phase. SPO activities will include updating baselines, and direction and concurrent support of testing and design review activities throughout the Acquisition Phase.

A sequential diagram indicating reliability program activities of the Acquisition Phase is shown in Figure 3-3. The activities indicated in



NOTES: Numbers in parentheses relate to block numbers in Figure 7 of AFSCM 375-4.

= Primarily Air Force responsibilities.

= Primarily Contractor responsibilities.

= Joint Air Force/Contractor responsibilities.

Figure 3-3. Reliability Program Activities During the Acquisition Phase

this diagram are related to general areas of SPO management activity, and keyed to corresponding blocks of Figure 7 of AFSCM 375-4. The reliability program activities indicated in Figure 3-3 are described in the following discussion of Acquisition Phase activities. The numbers in parentheses following each subject heading also refer to specific blocks in Figure 7 of AFSCM 375-4.

Several of the activities summarized below for system development during the Acquisition Phase are also applicable to non-system programs. The actual activities that should be included in such a program should be selected based on the requirements of the specific program. However, any development program should include reliability engineering support activities such as those discussed in paragraphs 6c and 6f. In addition, support should be provided in developing reliability test plans and in performing reliability demonstration testing (see paragraphs 6b and 6g).

a. Update Reliability Factors of Design Requirements Baseline (4). The most significant activities in initiating the Acquisition Phase insofar as the SPO reliability program is concerned, are those involving the updating of the Design Requirements Baseline to reflect changes required by the System Program Directive. Particular emphasis should be placed on the requirements for compatibility between the Part I Detail Specifications and the System Specification. Review and updating of reliability requirements of the Design Requirements Baseline is a system engineering activity. However, these activities are performed in support of, and are directly controlled by configuration management.

b. Reliability Program Support in Developing Category I and II Test Plans (5 and 8). The responsibility for Category I and II testing is assigned to the SPO Deputy Director for Test and Deployment who appoints Air Force test directors who will be responsible for the coordinated development of category I and II test plans, and the organization of a field test force for conducting category II testing.

   Reliability testing is a major factor in the category I and II test programs. In fact, the importance of reliability testing is emphasized by the separate paragraph specifically covering reliability testing in both the System Specification and the Part I Detail Specifications (see Exhibits I and II of AFSCM 375-1). Therefore, reliability testing requirements should be a major factor in the subsequent test program planning activities. In many instances the scope of reliability testing requirements will justify the appointment of reliability specialists on the field test force and, for very

large systems for which reliability achievement is a major development criterion, a reliability specialist could be included on the immediate staff of the Deputy Director for Test and Deployment. In any event, the reliability specialists of the System Engineering Division should fully support the Deputy Director for Test and Deployment by providing technical information concerning reliability testing and test facility requirements.

c. Preliminary Reliability Engineering by Contractor (11). One of the development contractor's early activities is to evaluate and update the reliability program plans and schedules which were included in his Phase B final report, and prepare his working plans for providing reliability capabilities for the development activities.

The development contractor's reliability engineering effort begins as a continuation of the system engineering effort performed during the Conceptual and Definition Phases. The earlier detail design efforts which were primarily directed toward apportionment of reliability requirements to CEI's will now be directed toward development of an acceptable design approach. Reliability factors of the preliminary detail designs for CEI's will be developed based on the reliability requirements of the approved Part I Detail Specifications.

As the design progresses, new requirements will be identified, many of which will involve areas of development that are directly influenced by the results of the reliability engineering and trade-off activities. For example, reliability data in the form of expected failure rates is a major factor in developing end item maintenance features, as well as in allocating maintenance spares. In addition, early reliability engineering and analysis inputs are essential in preparing for subsequent Preliminary Design Reviews (PDR), Critical Design Reviews (CDR), and indirectly the First Article Configuration Inspection (FACI).

d. Reliability Specialist Support of PDR (13). The contractor's preliminary detail designs are reviewed on an incremental basis as the preliminary design of each CEI is completed. This Preliminary Design Review (PDR) is performed to determine that the design approach is feasible and sound, and that the performance requirements specified in Part I Detailed Specification can be met. A successful PDR normally is a prerequisite to continuing with detail design efforts.

The review should include an assessment of updated reliability, modeling, allocation and prediction data, as well as reliability

design features. (See Chapter 6 for a discussion of reliability design review.) In order to properly evaluate reliability engineering factors, a reliability specialist should be included on, or available as a consultant to the PDR representation of both the contractor and procuring activity.

e. Validate Reliability Requirements of Part I Detail Specifications (14). Based on the findings and recommendations of the PDR, the contractor usually will update and validate the Part I Detail Specifications before proceding with his detail design activities. The reliability requirements of the specifications will be of particular interest because any specification revision in response to the PDR can effect CEI reliability even though the revision is performed to correct deficiencies in other areas. Therefore, each revision to the Part I Detail Specifications should be evaluated with respect to its impact on CEI and system reliability.

f. Provide Reliability Engineering Support to Detail Design Activities (15). Following the validation of the Part D Detail Specifications as a result of PDR actions, the contractor initiates a concerted detail design effort which will result in test and production hardware and facilities meeting the specified requirements.

The primary function of the contractor's reliability program during the detail design effort is that of monitoring and evaluating the design as it progresses to assure that the specified level of reliability is being achieved. This should include a continuing effort to update the reliability model and documentation to reflect details of design as they are defined, and to perform periodic reliability predictions to detect design problem areas at the earliest possible time. In addition, the reliability specialist should provide support in the application of reliability improvement techniques such as those discussed in Chapter 11.

g. Prepare Category I Test Procedures and Perform Tests (18, 19 and 20). As the detail design progresses, the category I test plan is expanded and category I test procedures are prepared to include detail system, subsystem, CEI and component reliability tests. (See Chapter 10.) The reliability test plans and procedures are then implemented as part of the category I testing to comply with the quality assurance provisions of the Part I Detailed Specifications.

The contractor's category I test procedures should include reliability design analyses and demonstration to determine compliance with the quantified reliability requirements as specified in the Part I Detail Specifications (see Exhibit II of AFSCM 375-1). In a typical case, however, the reliability demonstrations should be

conducted concurrently with other operational tests in order to reduce the total cost and time requirements for completing the category I test program.

h. Evaluate Reliability Engineering Data for CDR (21). The results of the detail design effort are reviewed to determine the adequacy of the design in meeting the requirements of the Part I Detail Specification. This Critical Design Review (CDR) considers reliability engineering and analysis data as a part of the overall engineering and design documentation rather than as a separate item. Therefore, the CDR does not include a "reliability review" as such. However, because of the importance placed on reliability achievement as a development objective, and in view of the specialized nature of reliability documentation, it is usually desirable to include reliability engineering representation on, or available for consultation to the CDR group.

   The CDR results in formal evaluation and identification of specific engineering documentation being prepared to govern full-scale production.

i. Review Reliability-Critical Aspects of the Part II Detail Specifications (23). The results of the development and review actions provide the Product Configuration Baseline which is documented in Part II, "Product Configuration and Acceptance Test Requirements" of the Detail Specification (see Exhibit II of AFSCM 375-1). This document does not include specific reliability requirements. However, its preparation should be subjected to the review and approval of the reliability specialist to assure that reliability factors of the design have not been compromised.

j. Provide Reliability Design Review Support to FACI (25). The First Article Configuration Inspection (FACI) is a critical inspection of the first article to be produced in accordance with the Part II Detail Specifications. This formal review is primarily concerned with production design characteristics and, as such, does not directly consider the reliability aspects of the design. However, minor discrepancies between the article as produced and the specification requirements are sometimes resolved by means of waivers in specification requirements. Approval of any such waivers should be subject to the review and approval of reliability specialists to assure that the CEI reliability is not compromised.

k. Prepare for and Conduct Category II Reliability Tests (28 and 35). The category II tests are intended to demonstrate compliance with the requirements of the System Specification and Part I Detail Specification, both of which contain explicit quantitative

reliability requirements. Therefore, a significant portion of category II testing should be devoted to the demonstration of achieved CEI, subsystem and system reliability. Since this is the only demonstration of total system reliability before turnover of the system to the using agency, the reliability demonstration conducted during category II testing must be considered as one of the major milestones of the reliability program. It is significant that the category II Final Test Report includes a report on the "functional reliability of the system," and that these reliability factors are given as much weight in the report as any of the system performance test results. See Chapter 5 and Data Item Number T-120 of AFSCM/AFLC M 310-1.

l. Support Development of Category III Reliability Tests (38). Category III testing is performed by the using command during the Operational Phase, to assess system effectiveness and reliability in the intended operational environment. Although actual testing begins in the Operational Phase, planning for the category III tests must be initiated earlier to allow for proper test support and scheduling. The responsibility for formulating the category III test plan and procedures rests with the using command. However, essential support in all technical and engineering areas is provided by the SPO.

Category III testing normally includes system effectiveness, operational readiness or other form of demonstration which requires an assessment of system and subsystem reliability. Therefore, reliability activities of the SPO should include support in developing the reliability evaluation and demonstration aspects of the category III test plans and procedures.

m. Perform Reliability Analysis During Technical Approval Demonstration (42). One of the major activities of the contractor in concluding the Acquisition Phase is the Technical Approval Demonstration (TAD), which is a demonstration to show that each CEI, each subsystem, and the complete system are acceptable in the configuration intended for turnover. Acceptability of the system reliability is normally measured in terms of a calculated quantity such as MTBF, or a predicted quantity such as the probability of mission success at a random point in time. In any case, reliability demonstration and prediction data as developed during earlier testing and analysis will provide a major input to the TAD.

7. RELIABILITY PROGRAM MANAGEMENT DURING THE OPERATIONAL PHASE

Reliability program management activities performed during the Operational Phase should be directed toward assuring the turnover of an adequately reliable system to the using command or organization. In general, these activities will include the completion of residual reliability engineering and testing, supporting the category III test program, performing reliability data analysis and evaluation, and providing reliability engineering support for modification programs.

The responsibility for reliability program management during the Operational Phase is transferred from the System Program Director of the SPO to the System Support Manager of AFLC. This transfer of responsibility is not abrupt, but rather is accomplished on an incremental basis as operating units of the system are accepted by the user.

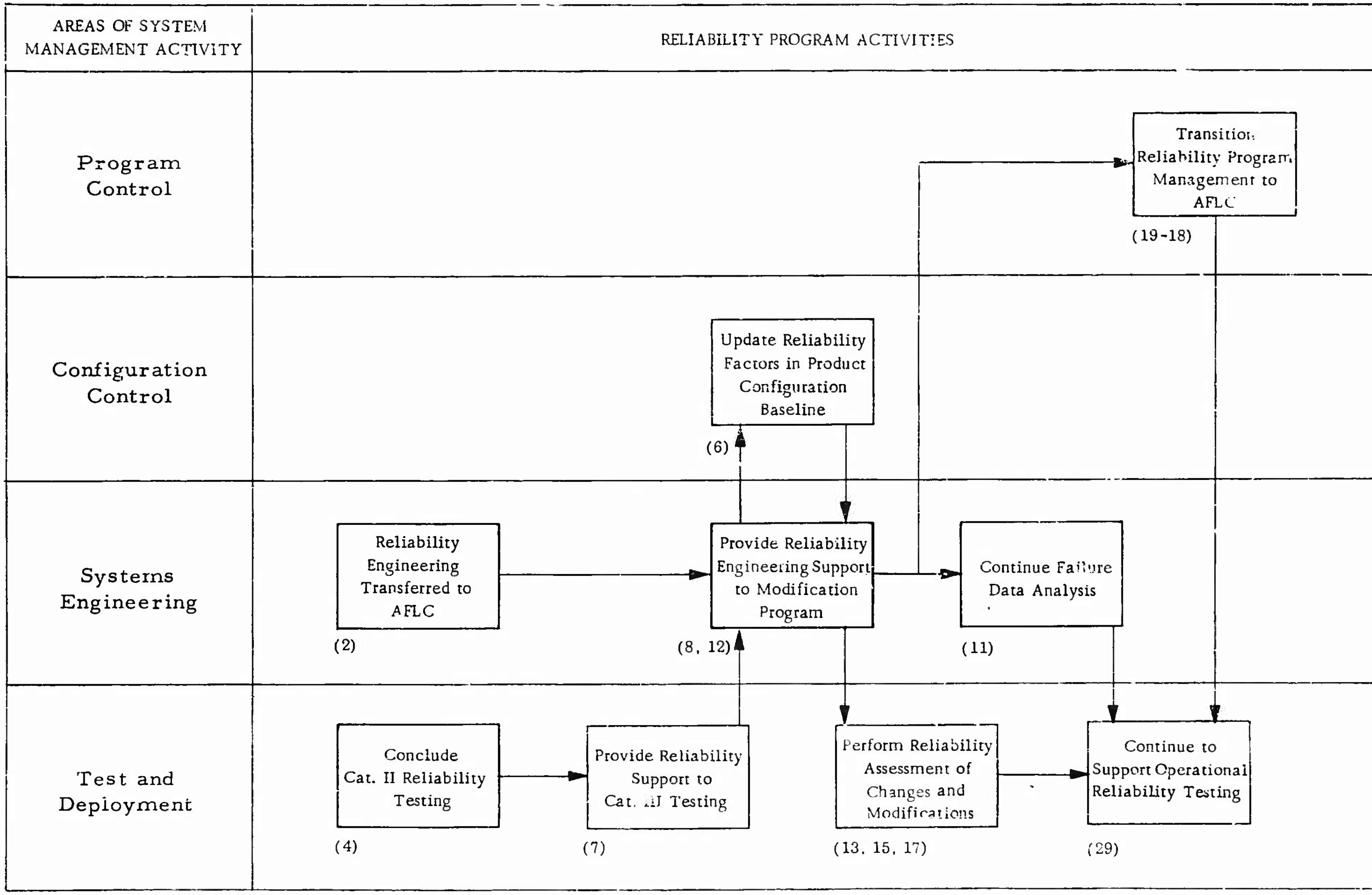
Typically, the Acquisition Phase and Operational Phase overlap to a considerable degree. The acceptance of the first operating unit by the using command initiates the Operational Phase, but the Acquisition Phase is not concluded until the last operating unit is delivered, tested, and turned over.

A sequential diagram indicating reliability program activities of the Operational Phase is shown in Figure 3-4. Activities shown in this diagram are keyed to corresponding blocks of Figure 9 of AFSCM 375-4.

The reliability program activities indicated in Figure 3-4 are described in the following discussion of Operational Phase activities. The numbers in parentheses following each subject heading also refer to specific blocks in Figure 9 of AFSCM 375-4.

The reliability program activities summarized below are directed toward a system program and all of these may not be directly applicable to non-system programs in all cases. However, many of these activities are applicable during the activation and operation of any new equipment item even though it is not identified as a system element. For example, reliability engineering support (see paragraph 7e) should be provided for modification programs associated with any equipment in the operational inventory. In addition, failure data analysis programs, as mentioned in paragraph 7g, are important, not only in evaluating the operation of a new equipment, but also in obtaining data applicable to development of other equipment items.

a. Reliability Engineering Transferred to AFLC (2). Following the contractor's successful completion of the Technical Approval Demonstration (TAD), and using command acceptance of hardware



NOTE: Numbers in parentheses relate to block numbers in Figure 9 of AFSCM 375-4.

Figure 3-4. Air Force Reliability Program Activities During the Operational Phase

items and facilities, the responsibility for operational engineering for the respective units is transferred to AFLC.

Operational engineering is performed to resolve service-revealed deficiencies, and to investigate other operational aspects of the performance and reliability of the system. Therefore, an important activity of operational engineering should be the analysis of failure data obtained via the Air Force Maintenance Data Collection System (see Chapter 7). In particular, system reliability evalutions should be performed using data derived from analyses of high system failures, and component/item data related to unsatisfactory reliability experience. Due to the emphasis on the investigation of system reliability problems it is apparent that reliability engineering should be a significant portion of the operational engineering function. Therefore, AFLC's responsibility for operational engineering includes the assumption of a portion of the system reliability program management responsibility.

b. Conclude Category II Reliability Testing (4). In the ideal case category II testing is completed prior to turnover of the first unit. However, in many practical cases category II testing extends into the early part of the Operational Phase to accommodate tests requiring long periods of data gathering. Reliability demonstration is one of the most common of such long-duration tests. Quite often, the desired level of confidence that the system reliability requirement is met can only be established by accumulating extensive operating time.

c. Update Reliability Factors in Product Configuration Baseline (6). System deficiencies revealed during category II testing are corrected by updating changes, some of which can be initiated after the start of the Operational Phase. Because of the extended time required for reliability demonstrations during category II testing, it is conceivable that updating changes extending into the Operational Phase will involve a significant amount of reliability engineering. Therefore, reliability support in developing changes and updating the Product Configuration Baseline should continue unitl the final change has been completed.

d. Provide Reliability Support to Category III Testing (7). Category III testing is started by the using command after the first operating unit has been accepted and after all operationally critical updating changes have been made. In general, category III tests include some form of reliability or system effectiveness demonstration that will be performed as a part of other operational testing and evaluation. Therefore, a separate reliability test may not be required. However, due to the specialized methods for analyzing

reliability data, the category III test force should either include a system reliability evaluation specialist, or appropriate specialized support should be provided by the SPO.

e. Provide Reliability Engineering Support to Modification Program (8 and 12). Deficiencies revealed during category III testing are corrected by means of modifications which are the responsibility of either AFSC or AFLC depending on the extent of the modification. AFR 57-4 defines two general classes of modifications that are of concern to the reliability program. These are class IV modifications to correct serious deficiencies and class V modifications to provide new mission capabilities.

   Class IV modifications that are within the capabilities of AFLC engineering will be the responsibility of the AFLC System Support Manager (SSM). Class IV modifications that are beyond the capabilities of AFLC engineering, and all class V modifications are assigned to AFSC. In the latter cases, the modification development is managed in accordance with the System Program Management procedures of AFSCM 375-5, beginning at the appropriate point in the Definition or Acquisition Phase. Such modification programs will require reliability program management activities similar to those discussed previously for a new system development program.

f. Perform Reliability Assessment of Changes and Modifications (13, 15 and 17). Follow-up development tests to evaluate updating changes and modifications are similar to category I or II tests, but are usually on a reduced scale. They are performed against specific revisions of the Design Requirements Baseline, and emphasize design aspects directly related to the change or modification. However, other tests including reliability assessment are required to assure that the modification did not adversely impact on other system characteristics. Quite often, empirical confirmation of reliability characteristics will not be practical during follow-up development testing due to the time required to obtain a statistically valid reliability measure. In this case, analytical procedures should be employed to assess the effect of the modification on the achieved system reliability.

g. Continue Failure Data Analysis (11). Data are collected on all operating units to reflect failure experience during installation and checkout as well as during operation by the using command. Failure occurring during checkout are reported on prescribed forms such as AFSC Form 258. After the units have been turned over to the using command the Maintenance Data Collection System as defined in AFM 66-1 is instituted and failure data are reported

using the AFTO-200 series forms as described in Chapter 7. Failure data feedback and analysis is a continuing activity that may not terminate until disposition of the system. These data are a primary input for system reliability analyses and other studies that are performed throughout the operational life of the system, and that provide historical reliability data essential to the development of future systems. The analysis and evaluation of failure data is one of the most significant activities of the reliability program following transition of the system engineering responsibility from AFSC to AFLC.

h. <u>Transition Reliability Program Management to AFLC</u> (14 through 28). At the conclusion of the final Acquisition Phase activities, all system management functions will have been transitioned from AFSC to AFLC. By this time, total Air Force engineering responsibility will have been assumed by AFLC. Therefore, any long-term reliability engineering function, such as failure data analysis and operational reliability evaluation will become the responsibility of AFLC engineering. Thus, AFLC will assume the continuing reliability program management responsibility for the system.

i. <u>Continue to Support Operational Reliability Testing</u> (29). Category III testing is completed by the using command in accordance with the previously prepared category III test plan. However, this does not conclude the system testing activity. A program to perform operational testing is continued until the system has been exercised under various conditions and loads, and within the constraints of a variety of missions. The system is tested on an incremental basis until all system elements have demonstrated acceptable performance in a variety of operating environments.

Such continued operational testing is justified by providing means for:

- Training operational personnel and evaluating their performance. (Note: Operating personnel are a part of the total system configuration, and are considered as basic elements in evaluating operational reliability.)
- Assessing system capability in view of changing threats.
- Identifying the need for system modification or a new system. (This is one of the inputs to the pre-conceptual requirements and planning studies for future generations of systems.)
- Permitting evaluation of the impact of new interfacing systems or changes to existing interfacing systems.
- Providing measures of system performance and reliability under operational stress.

The need for a continuing reliability program in realizing this last advantage is obvious. However, other areas, such as assessing system capability, identifying the need for modification, and evaluating interfacing impact also involve the consideration and evaluation of reliability factors. It is apparent, therefore, that reliability program activities will continue throughout the Operational Phase and into the Conceptual Phase of the next generation of systems, thereby completing the cycle.

CHAPTER 4

RELIABILITY ENGINEERING MANAGEMENT

1. INTRODUCTION

Chapter 3 has presented an overall discussion of the objectives and activities of Reliability Program Management in relation to the entire spectrum of system program management, including significant activities in the areas of configuration control, systems engineering, and test and deployment which directly relate to hardware development.

The ultimate objective of the reliability program is the acquisition of an appropriately reliable system. The required level of reliability is stated in the system specification as a part of the configuration control activity, and the achieved reliability is verified as a major activity of the test program. However, configuration control and testing cannot "achieve" reliability. Reliability achievement is the unique responsibility of reliability engineering. In fact, without an effective reliability engineering program, the reliability assurance activities associated with the configuration control and testing program will be meaningless. Therefore, an effective reliability engineering program is an essential aspect of the total systems engineering process. Furthermore, an effective reliability engineering program can only be assured by the timely and appropriate management activities throughout the life cycle of system development.

Specific considerations in the management of an effective reliability engineering program are discussed in this chapter. This discussion is presented within the concepts of the Systems Engineering Management Procedures of AFSCM375-5, but also relates specific management activities to other less comprehensive development programs where the complete systems engineering approach is not warranted.

Reliability engineering encompasses a variety of engineering design and analysis disciplines which are applicable at all levels of system design and development as an integral part of the total system engineering process. As a defined program, reliability engineering begins with the initiation of the system engineering activities performed by the SPO cadre during the conceptual transition stage of the Conceptual Phase. This does not imply that important reliability program activities are not performed earlier. In fact reliability achievement can be a major objective of the technological development activities of the early Conceptual Phase. However, these earlier activities are generally developmental rather than engineering-oriented and, therefore, will not be discussed in this chapter.

Reliability engineering typically is initiated as an element of the system-engineering activities during Conceptual Transition, and continues throughout the Definition and Acquisition phases and into the Operational phase. In general, reliability engineering encompasses two areas of activity: (1) reliability achievement activities which include part selection, derating, redundancy design, and other engineering activities directed toward the design of a reliable product; and (2) reliability assurance activities which include the allocation, specification and verification of compliance with reliability requirements.

It is the responsibility of reliability engineering management to assure an effective reliability engineering program during all phases of the system life cycle. In view of this, the balance of this chapter is directed toward a summary of reliability engineering activities that are performed during the various phases of a typical system development program. This discussion is presented within the concepts of the Systems Engineering Management Procedures of AFSCM 375-5. However, many of the activities described are applicable to any development program, including hardware procurement and experimental model development programs such as those performed in-house by RADC, and which do not fall within the system engineering concepts.

2. RELIABILITY ENGINEERING MANAGEMENT DURING CONCEPTUAL TRANSITION

The responsibility for system reliability engineering management during the Conceptual Phase is normally assumed by the System Program Manager upon receipt of the SOR/OSR/ADO and initiation of Conceptual Transition. Thus, the SPO cadre that is established at this time should include, as a part of the systems engineering activity, an element (at least one person) having the overall responsibility for initiating and conducting the reliability engineering program. This element will assume the reliability engineering responsibilities under the Deputy Director for Engineering of the SPO upon initiation of the Definition Phase.

The primary objective of the reliability engineering program activities during Conceptual Transition is to establish the overall system reliability requirements, allocate these requirements to the major system functions and from this develop the reliability requirements input for the PTDP. Several specific activities have been defined for meeting this objective. These activities are summarized in Table IV-1, where specific reliability engineering activities are identified together with the purpose of the activity, general source of input data, type of output, and specific use of output data. The engineering techniques used and other information relating to each activity identified in Table IV-1 are summarized in the following paragraphs.

Table IV-I. Air Force SPO Cadre Reliability Engineering Activities-Conceptual Phase

Activity	Purpose	Input Data Source	Outputs	Where Used
• Review Source Documentation	• Identify information and data relating to Reliability Engineering	• SOR/OSR/ADO • Conceptual System Study Reports. • Feasibility Study Reports • Technological Development Reports	• List of relevant documents, identified by: - Type of information - Identification of Documents - Location within the document	• In support of all subsequent Reliability Engineering Activities
• Quantify System Reliability Requirement	• Provide a gross Reliability Goal for overall system	• System effectiveness/ availability requirements • Mission time Profile Data • Gross constraints (maintainability, etc.) • Preliminary trade study data	• Quantified Reliability Requirements for overall system (MTBF, R(t), etc.)	• Initial Reliability Allocation Studies • PTDP
• Develop Reliability Block Diagram and Model	• Provide basis for Trade Studies, Reliability Allocations, and all subsequent Reliability Engineering Activities	• Functional Block Diagrams • System Reliability Requirements • Preliminary Reliability Predictions	• Reliability Block Diagram and Mathematical Model for overall system, defined down to first level functions	• Reliability Allocations • Trade Studies • PTDP
• Perform Initial Reliability Allocations	• Provide Gross Reliability Requirements for major system functions	• Quantified System Reliability Requirement • Top-Level and First-Level Functional Diagrams • Reliability Prediction Data	• Quantified Reliability Requirement or Goal for individual system functions • Reliability Engineering Program Requirements	• Requirements Allocation Sheet (RAS) • Trade Study Reports • PTDP
• Develop Reliability Design Requirements	• Provide Reliability Input to Program Requirements Baseline	• RAS • Trade Study Reports • Time-line Sheets	• Quantified Reliability Requirements for identifiable subsystems, etc.	• Design Sheets • PTDP

2.1 Review of Source Documentation.

The initial activity of the Conceptual Transition phase is that of reviewing available source documentation to identify all information and data that will relate to the subsequent reliability engineering activities. As a minimum, this review should be directed toward identifying sources of data relating to the following factors:

a. Mission profile descriptions, indicating factors from which system reliability requirements are developed. This includes data relating to system operating time requirements in each mode of operation, and any other factors that will aid in defining the time constraints that will be imposed on the system.

b. System functional requirements for each defined mission. This includes information identifying system functional configuration in each mode of operation, and an assessment of the probable operational consequences in the event of loss of any given system function.

c. Any constraints that may limit, or place excessive demands on system reliability. This includes such constraints as maintainability limitations, and other factors that may impact on the definition and allocation of reliability requirements.

d. System effectiveness, availability, operational reliability, and other requirements of the system that include reliability as a parameter, and which will facilitate quantification of system reliability requirements.

2.2 Quantification of System Reliability Requirements.

Following the effort to gather and review source data, the reliability engineering program begins with the initial quantification of the gross reliability requirements for the system. At times, system reliability requirements are stated in the SOR/OSR/ADO documents and need only to be updated and verified at this time. In general, however, the system reliability requirements must be derived by interpretation of qualitative statements concerning the intended mission, and gross quantifications of system effectiveness, operational reliability, or availability requirements. These latter factors are functions of reliability, maintainability, and other parameters which must be considered in establishing the design goals for the system. However, there is considerable latitude for trade-off between the various parameters before the system design goals can be optimized.

The task of quantifying the overall system reliability requirements generally involves a trade-off between maintainability (mean time

to restore, maximum allowable repair time, probability of restoration within a given time, etc.) and reliability (mean time between failure, probability of survival, etc.), together with other parameters, including operational characteristics and cost factors. Thus, this initial development of system design goals involves a gross allocation of the various parameters contributing to the achievement of system effectiveness.

Techniques employed in the trade-off between reliability, maintainability and other parameters in establishing reliability specification requirements are reviewed in Chapter 6. Some additional techniques for interpreting mission requirements in terms of reliability goals are summarized in Chapter 8.

2.3 Development of Reliability Block Diagram and Model.

The initial reliability block diagram and mathematical model, as developed during Conceptual Transition, forms the basis for all subsequent reliability engineering program activities. Therefore, this task of developing the initial block diagram and model is one of the more important of the early reliability engineering activities.

The initial reliability block diagram is generally structured to define functional relationships, and is essentially a refinement of the top-level and first-level functional diagrams which are modified to include the gross reliability requirement, and the results of some early reliability predictions that can be performed at this time. As the reliability engineering program progresses, the model is revised and updated until reliability factors relating to individual elements of system hardware can be related to overall system reliability, as well as to the other parameters of system effectiveness.

2.4 Initial Reliability Allocations.

The gross reliability allocations performed during the conceptual phase are directed toward the assignment of a feasible reliability goal for each function as defined on the functional diagram. These allocations are performed using preliminary reliability prediction techniques, such as the reliability prediction by function techniques discussed in Chapter 9, and are verified using the initial reliability model to assure that the levels of reliability, as allocated, are appropriate in relation to the required total system reliability.

The results of the reliability allocation are used in developing reliability design requirement statements to be included in the initial requirements allocation sheets (RAS). These documents are prepared

as a part of the system engineering activity and provide one of the primary technical inputs to the PTDP. The results of the allocation studies are also important inputs to the reports describing Conceptual Phase trade study activities.

2.5 Reliability Design Requirements.

The final major activity of the reliability engineering program during Conceptual Transition includes preparing the reliability design requirements that will ultimately appear in the System Specifications. At this stage, these requirements are stated in specification language and are incorporated into Design Sheets which become a part of the PTDP. Thus, the reliability design requirements form a part of the Program Requirements Baseline governing the activities of the Definition Phase.

3. RELIABILITY ENGINEERING MANAGEMENT DURING PHASE A OF THE DEFINITION PHASE

Upon initiation of the Definition Phase, the full SPO is established and the Deputy Director for Engineering assumes responsibility for all subsequent system engineering activities. This includes all activities associated with reliability engineering.

Phase A of the Definition Phase includes those system engineering activities by the SPO that are necessary in preparing a request for proposals (RFP) for Contract Definition (Phase B). Additional system engineering is performed by each of the competing contractors in preparing their proposals, and final engineering analyses are performed by the SPO in evaluating the various proposals in preparation for award of the Definition Contract.

The reliability engineering activities as discussed here are those performed by the SPO in support of the RFP development, and in evaluating proposals that are prepared in response to the RFP. These activities are summarized in Table IV-2. The engineering techniques used, and other information relating to each activity are summarized below. In addition, typical reliability engineering activities that might be performed by a prospective definition contractor in preparing his proposal are reviewed with reference to the impact on the SPO reliability engineering activities in concluding Phase A.

3.1 Expanding Reliability Requirements.

Following the authorization to begin the Definition Phase, a significant amount of system engineering is necessary in determining additional design requirements and performing trade-off studies as

Table IV-2. Air Force SPO Reliability Engineering Activities-Phase A Of Definition Phase

Activity	Purpose	Input Data Source	Outputs	Where Used
• Expand Reliability Requirements	• Update System Reliability Requirements	• Approved PTDP • Second Level Functional Diagrams • Updated RAS, and Design Sheets	• Reliability Requirements allocated to defined subsystems	• Expanded "Design Requirements" column of RAS • Expanded Design Sheets
• Determine Requirements for Additional Development	• Define Reliability Engineering Activities remaining to be performed	• Trade Study Reports • Updated Reliability Block Diagram • Approved PTDP • Expanded Reliability Allocations	• System Reliability Requirements remaining to be defined during: - Proposal Development - Contract Definition	• Statement of work for Contract Definition RFP
• Prepare Reliability Input for System Specification	• Provide System Reliability Objectives for Phase B	• Updated RAS • Updated Design Sheets • Updated Reliability Model	• Quantitative Reliability Requirement for system and defined subsystems	• Paragraph 3.1.3.1 of System Specification
• Initiate Reliability Test Plan Development	• Provide Reliability Test Program Requirements	• Quantitative Reliability Requirements • System performance test plans	• Preliminary Reliability Testing Plans (Cat. I & II) • Test Program Requirements • Test Data Requirements	• Paragraph 4.1.3 and 4.2 of System Specification
• Prepare Reliability Input for RFP	• Insure Adequate and Valid Reliability Engineering Program Requirements	• System Specification • Additional Reliability Engineering Requirements	• Statement of Reliability Engineering Program Requirements to be imposed during Phase B	• RFP for Phase B

required for the preparation of the initial System Performance/ Design Requirements General Specification (System Specification). These activities result in expanding the functional diagrams to include second-level functions, and respective expansion of the RAS and Design sheets. As these systems engineering activities progress, the reliability requirements must also be updated and expanded as appropriate.

The reliability engineering efforts required to support these system engineering activities includes the expansion of the reliability block diagram and model to reflect the additional information presented in the updated functional diagrams. The expanded model is then utilized for further allocating the quantified reliability design requirements to the newly defined elements of the system. In general, this allocation is still related to functional rather than physical subdivisions of the system and, thus, will involve the application of reliability prediction procedures similar to those used in the initial allocation. In some cases, however, system functions may be defined to the extent that prediction procedures considering more detailed parameters such as equipment complexity can be utilized.

The results of this refinement and expansion of the reliability allocation are used in providing reliability design requirements for the expanded RAS's and Design sheets.

3.2 Determining Additional Reliability Engineering Requirements.

The reliability engineering activities during the early stages of Phase A not only provide updated system reliability requirements information, but also permit the identification of the additional reliability engineering activities that will be necessary before the system is completely defined. In general, these additional requirements can be categorized as either (1) those that can be expected to be satisfied as a result of the proposal development efforts of the contractors who are competing for the Definition contract, and (2) those that will require the more extensive engineering efforts of the actual contractor Definition (Phase B) activities. These additional requirements will be included in the proposal preparation instructions and statement of work accompanying the Phase B RFP.

3.3 Preparing Reliability Requirements Input for Initial System Specifications.

The updated system reliability requirements are prepared in the appropriate specification language. This will involve the application of techniques such as those described in Chapter 6 and 10 for

specifying reliability, and will be prepared in the format required for direct use in the System Specification. (See Exhibit I of AFSCM 375-1.)

3.4 Initial Development of Reliability Test Plan.

A reliability test plan, compatible with the system reliability requirements is initiated during this phase, and is refined as the system reliability requirements are updated. This initial plan will identify the general testing requirements, as applicable during the Category I and Category II testing programs, and to the extent required for guiding the subsequent test plan development efforts of the Definition Phase contractors. The initial reliability test plan should be considered in preparing the wording for the reliability test requirements paragraph of the System Specification. (See Exhibit I of AFSCM 375-1.) Engineering considerations in the development of reliability test plans are discussed in detail in Chapter 10.

3.5 Reliability Inputs for Phase B RFP.

The results of the SPO reliability engineering activities during Phase A provide the information necessary for preparing the reliability requirements input to the Phase B RFP. As a minimum, this should include the preparation of definitive statements concerning:

a. Reliability requirements, constraints, and other considerations in conducting trade studies during Contractor Definition.

b. Test program requirements for demonstrating reliability factors as allocated to the defined system elements.

c. Any incentive recommendations that would be of concern to the contractors' reliability engineering efforts. This includes the identification of high-risk areas to serve as a basis for development of incentive provisions.

3.6 Contractors' Reliability Engineering Activities During Phase A.

During Phase A of the Definition Phase, the prospective definition contractors will perform a series of system engineering studies and analyses as necessary to provide input to their Contract Definition proposals which are prepared in response to the RFP. These engineering activities will be governed by the specific requirements of the RFP and System Specification, and usually will include a significant reliability engineering effort. Some of the typical activities

are summarized below. These actions are discussed to illustrate the contractors' reliability engineering iterations rather than to identify specific procedures that the contractor is required to follow.

a. Review RFP Documentation. The initial efforts of the contractors' reliability engineers should be to review the RFP, and all documents that accompany the RFP to identify all system reliability design requirements, and establish an approach to the development of the reliability engineering and test program.

b. Expand and Update System Reliability Data. The updated reliability block diagram, requirement allocation sheets, system specification, and other data relating to the reliability engineering effort should be expanded, refined, and updated to the extent possible with relation to the system reliability requirements.

c. Verify Reliability Requirements. Based on the updated data, the contractor should verify the reliability requirements, including test program plans and, where necessary, should interpret such requirements in terms of his proposed approach. Any apparent or real deviation from the requirements of the RFP should be fully explained and justified.

d. Provide Inputs to Contractor's Proposal. The reliability engineering activities are concluded with the preparation of inputs to the contractor's proposal for the Phase B Definition effort. Specific inputs should include at least the following:

- A discussion to demonstrate the contractors full understanding of the system and end item reliability requirements and reliability program objective.

- A reliability program plan, summarizing the contractor's approach to the reliability engineering and analysis tasks during the Contractor Definition program.

4. RELIABILITY ENGINEERING MANAGEMENT DURING PHASE B OF THE DEFINITION PHASE

Phase B of the Definition Phase involves essentially contractor activity with the SPO system engineering activity providing guidance and support to the participating contractors, and periodically reviewing the results of the system engineering activities. Formal reviews of system requirements and system design are performed periodically during a typical

contractor Definition program. Three of these are associated with the development of the Part I Detail Specifications for CEI's, and directly involve the participation of the SPO reliability engineering activity. Other reviews are concerned with the parallel development of end item maintenance design, and are generally of secondary interest to the reliability engineering program. The three reviews requiring direct participation of the reliability engineering activity of the SPO are summarized in Table IV-3. Specific activities in relation to a typical definition program are reviewed in the following paragraphs.

4.1 System Requirements Review of Operation's Functions Development.

The initial review by the SPO is performed to evaluate the contractors effort to define the system requirements in terms of operations functional diagrams, RAS's and time-line sheets. The contractors' reliability engineering activities to this point will typically include the development of refined and updated RAS's, and design sheets, and the performance of related trade studies. These activities will have been centered around an updated and refined reliability block diagram and mathematical model, which, in turn, will reflect the latest expansion of the functional diagram. During the SPO review of documentation generated during these contractor activities, particular attention should be given to:

a. Verifying the allocations of reliability and the means by which such allocations were performed.

b. Assuring the completeness and accuracy of reliability associated functions.

c. Verifying reliability block diagrams and mathematical models.

d. Assuring the adequacy of the contractor's design and hardware concepts.

4.2 System Requirements Review of End Item Selection.

The next series of contractor reliability engineering activities are directed toward the development of detailed reliability requirements for specific end items as the various items are selected. The systems engineering activities associated with this selection include a series of trade studies and the development of design requirements for each CEI. The results of these activities are documented by means of expanded and updated RAS's, schematic block diagrams, and design sheets, and by means of trade study reports as appropriate. In reviewing these documents, the SPO reliability engineering specialist should give particular attention to:

Table IV-3. Air Force SPO Reliability Engineering Activities-Phase B Of Definition Phase

Activity	Purpose	Input Data Source	Outputs	Where Used
. Review System Reliability Requirements (Operations Functions)	. To Review Contractors Initial System - level reliability engineering efforts to assure that engineering decisions are recorded and that technical direction is understood	. Updated (third - and possibly fourth-level) Functional Diagrams . Updated RAS's . Updated time-line sheets	. Evaluation of Contractor' progress in the initial Phase B reliability engineering efforts	. Feedback to the SPO
. Review System Reliability Requirements (End item Selection)	. To assure that the equipments selected to perform operations mission will meet reliability requirements.	. Updated Systems Engineering Documentation, including - functional diagrams - RAS's - Schematic Diagrams - Design Sheets - Inventory Equipment Requirements - Trade Study Reports - Time Line Sheets - Reliability Block Diagram Model and Allocations	. Evaluation of Contractors' efforts to date . Verification at identified high-risk areas in meeting reliability goals and schedules	. Feedback to the SPO
. Review System Reliability Design	. Assure Adequacy of Contractors' Reliability Engineering Activity during Phase B	. Updated Systems Engineering Documentation, including: - Functional Diagrams - RAS's - Trade Study Reports - Schematic Diagrams - Time-Line Sheets . Newly Developed Part I Detail Specifications	. Evaluation of Updated Reliability allocations, CEI Reliability Requirements, and Cat. I and II Reliability Test Plans	. Feedback to the SPO

a. Assuring that reliability requirements for end items are stated in engineering terms, and are compatible with the previously development system function reliability requirements.

b. Assuring that each design sheet includes appropriate reliability design and test requirements.

c. Assuring that the reliability test and demonstrations are consolidated with the other Category I and II tests to the maximum extent possible.

4.3 System Design Review.

The final review of interest to the SPO reliability engineering activity is concerned with the results of the reliability engineering activities performed during the development of the Part I Detail Specifications for the CEI's. In a typical systems engineering program the contractor will have performed a series of iterative engineering activities directed toward the definition of design requirements for specific end items, and will have documented the results of these activities by means of further updated and expanded RAS's, and schematic block diagrams. In addition, the design sheets will have been translated into the initial Part I Detail Specifications for contract end items (see Exhibit II of AFSCM 375-1).

The primary purpose of the reliability engineering input to this design review is to determine whether the reliability requirements as presented in the Detail Specifications are valid, and are in consonance with the program requirements baseline as originally established by the System Specification. This review should include at least the following:

a. An evaluation to assure that the reliability design requirements, as specified in the Part I Detail Specifications are consistent with the system development objectives, and are adequate and valid as a design requirement.

b. An evaluation of the reliability test and analysis requirements as stated in the Part I Detail Specifications. This should verify that a reliability test and analysis requirement is specified for each reliability design requirement, and that the test plan and acceptance criteria will verify compliance within the desired level of confidence. (See Chapter 10.)

5. RELIABILITY ENGINEERING MANAGEMENT DURING PHASE C OF THE DEFINITION PHASE

Phase C of the Definition Phase is concerned with the SPO's review and evaluation of the definition contractors' final reports and proposals for the acquisition phase development program. This review and evaluation is directed toward determining the technical soundness of the defined system, assuring the adequacy of the identification of high risk areas, and determining the degree to which the technical tasks specified in the RFP have been accomplished. In addition, when major advantage would accrue, an engineering synthesis is made of the best features of each proposed system to obtain an optimum system within the overall performance, cost, and schedule requirements and proprietary limitations.

The reliability engineering activities during this phase include a final review and evaluation of the reliability engineering aspects of each final report and proposal (see Table IV-4). This will include evaluation of the reliability requirements and test provisions as stated in the following documentation:

a. The Updated System Specification.

b. Updated and expanded reliability block diagrams and mathematical models (in relation to updated functional block diagrams).

c. Requirements allocation sheets.

d. Part I Detail Specifications.

e. Contractor's reliability program management plan.

f. Contractor's reliability test and demonstration plan.

g. Contractor's proposal for the Acquisition Phase, including reliability engineering techniques and procedures on his statement of work, and related schedules, costs, incentive features, etc.

The results of this evaluation, synthesis, and supplementation of contractor's results are reflected in the revised PTDP, which now becomes the Proposed System Packaging Plan (PSPP). This document provides the technical input to the Design Requirements Baseline governing the system development activities of the Acquisition Phase.

Table IV-4. Air Force SPO Reliability Engineering Activities-Phase C Of Definition Phase

Activity	Purpose	Input Data Source	Outputs	Where Used
. Technical Evaluation of Final Reports and Proposals	. Determine Adequacy of Reliability Aspects of Final Reports and Proposals	. Each Contractor's Reliability Engineering Documentation, including Reliability Input to: - Updated System Spec. - Functional Diagrams - RAS's - Time-Line Sheets - Trade Study Reports - Updated Reliability Block Diagrams and Models. - Reliability Predictions - Part I Detail Specifications - Schematic Diagrams	. Determination of the Degree to which each Contractor's Reliability Requirements Development meet Program Requirements . Reliability Input for Synthesis of best features of each Contractor's Design Approach into an Optimum System	. Design Requirements Baseline (Part I, PSPP, and Documentation)

6. RELIABILITY ENGINEERING MANAGEMENT DURING THE ACQUISITION PHASE

The purpose of the Acquisition Phase is to accomplish the delivery, installation and checkout of system elements, and their integration into an operable system. In effect, the Acquisition Phase is divided into two overlapping efforts; development and production. The development effort is a continuation of the system design activity of the Definition Phase, and continues through the final development and approval of the Part II Detail Specifications for Contract End Items (CEI's). This document establishes the technical requirements for the Product Configuration Baseline that governs production. The production effort includes the actual production of items on contract, together with the installation, checkout and acceptance testing of all such items.

The reliability engineering activities during the Acquisition Phase are included as a part of the development contractor's system engineering and design engineering responsibilities. Therefore, the SPO's reliability engineering activities take on a role of monitoring and reviewing the contractor's reliability design review and reliability test and evaluation efforts to assure that the design is meeting the specification requirements.

6.1 Reliability Engineering Support of Design Reviews.

During the Acquisition Phase, the contractor is required to perform a number of formal system requirements and design reviews directed toward verification of operations and maintenance equipment and facilities design. The particular reviews that are most significant in the system development engineering effort, and that are of major concern to the reliability engineering activity are the Preliminary Design Reviews (PDR), the Critical Design Reviews (CDR), and the First Article Configuration Inspections (FACI). In general, the responsibility of the SPO reliability engineering activity preceding and during these reviews includes the following:

- Reviewing previously developed engineering data to identify reliability engineering items that should be included in the review.

- Evaluating contractor prepared review schedules and agenda to identify items relating to the reliability engineering program, and to verify that all high-risk reliability engineering items, as identified in previous reviews and documentation, are being considered.

- Making recommendations as appropriate concerning the contractor's assignment of reliability engineering specialists to the review panel.

- Providing reliability engineering support as necessary when active participation of the SPO in review meeting is planned.

- Evaluating reliability-related aspects of minutes to review meetings.

- Evaluating all Engineering Change Proposals (ECP's) evolving from the review to assess the impact on end item and system reliability.

- Providing reliability engineering guidance and support to the SPO in decisions concerning approval of such ECP's.

Specific activities of SPO reliability engineering in association with specific PDR, CDR and FACI programs are dependent on the requirements of the particular development program and on the specific activities of the contractor in preparing for and conducting the reviews. Typical objectives and activities of contractor's reliability engineering groups in preparing for and supporting these reviews, are summarized in Table IV-5. This summary, and the more detailed discussions in the following paragraphs will provide guidance in planning the activities of the SPO reliability engineering program during the Acquisition Phase.

a. Preliminary Review of Reliability Design. The first defined activity of the SPO Systems Engineering following the formal initiation of the Acquisition Phase is the support and/or participation in the Preliminary Design Review (PDR). This formal technical review of the basic design approach for each CEI is usually performed by the contractor based on review criteria and agenda approved by the SPO. The responsibility of the SPO in the PDR can vary from active participation in the review meetings to a monitoring action involving evaluation and approval of the minutes of the review.

   One of the important aspects of the PDR is the evaluation of the engineering design approach to assure that the CEI reliability will satisfy the reliability requirements as established by the updated System Specification and the Part I Detail Specifications. In general, separate design reviews are not justified for each separate engineering discipline. Instead, reliability specialists are included on the design review panel and reliability

Table IV-5. Reliability Engineering Activities-Acquisition Phase

Activity	Purpose	Input Data Source	Outputs	Where Used
. Preliminary Review of Reliability Design.	. Evaluate reliability aspects of basic design approach for CEI's.	. Part I Detailed Specifications . Pre-design drawings, schematic diagrams, review of functional characteristics, etc . Updated functional block diagrams. . Reliability block diagrams and models. . Reliability predictions.	. Formal identification of documentation establishing reliability design factors of the CEI in relation to other system elements. . Demonstration of the compatability and integrating of selected reliability design with the requirements of the Part I Detail Specifications. . Review of reliability test/demonstration criteria and plans.	. Input to Preliminary Design Review (PDR).
. Critical Review of Reliability Design.	. Confirm reliability design of CEI's before committing design to production.	. PDR Minutes. . Part I Detailed Specifications. . Design Drawings. . Mock-up, breadboard or prototype test data when available. . Updated reliability block diagrams, models and predictions. . Proposed Part II Detailed Specifications.	. Determination whether detailed reliability design satisfies Part I Detail Specifications requirements. . Verification of inputs to Part II Detailed Specifications for production.	. Input to Critical Design Review (CDR).

Table IV-5. Continued

Activity	Purpose	Input Data Source	Outputs	Where Used
. Reliability Input to FACI.	. Confirm achievement of required reliability by production processes.	. Approved Part II Detailed Specifications. . Engineering drawings, and other design data. . Item on which FACI is to be performed.	. Verification that designed reliability is not degraded by design changes to facilitate production.	. Support for FACI.

design is evaluated as an integral part of the CEI design. However, an analytical evaluation of the reliability design is usually performed prior to the PDR in order to develop the necessary inputs to the review. This evaluation will normally be performed by the contractor. However, the SPO can elect to participate in order to monitor these activities, especially when high-risk areas or complex designs are being evaluated. Typical reliability engineering activities performed by the contractor for the purpose of developing impacts for the PDR include:

- Identification of reliability design factors that must be considered in establishing the agenda and schedules for the PDR.

- Identification of high-risk areas in reliability design that should be emphasized during the review.

- Assessment of the level of CEI reliability being achieved by the preliminary engineering design. Typically, this assessment will involve the performance of reliability predictions based on updated reliability block diagrams and models and reflecting the latest refinements of design data. (See Chapter 9).

- Evaluation of reliability test program plans to assure that the latest revisions in systems and CEI reliability requirements are reflected in the updated plans for Category I and Category II test programs.

b. Critical Review of Reliability Design. The next formal activity that is of direct concern to the SPO reliability engineering activity is the Critical Design Review (CDR), which is performed at the time the detailed design is essentially complete. This formal technical review is performed to evaluate the final design prior to committing the design to production. This includes a critical evaluation of the Part II Detailed Specification, which are the "build to" specifications that will subsequently form the technical input to the Product Configuration Baseline for production.

The reliability engineering input to the CDR follows essentially the same general procedures as for the PDR's, but should be more critical in that they are the final review prior to production. Typical reliability engineering activities that should be performed in performing this review, and developing inputs for the CDR are:

- Identification of reliability design factors that should be considered in establishing the agenda and schedules for the CDR. This should especially include those factors that had been identified as high-risk or problem areas during the PDR.

- Identification of critical reliability design factors that should be given particular attention during production.

- Assessment of the effectiveness of reliability engineering and related engineering design activities performed during the detail design program. This includes the critical review of the results of activities such as detailed reliability apportionment analyses, stress analysis reliability predictions, tolerance and degradation analyses, failure modes and effects analyses, derating, reliable parts selection, and low-level redundancy design.

- Assessment of the level of CEI reliability being achieved by the final design. This assessment should involve the most detailed reliability analysis, and, typically, would include consideration of details of design to the part (or equivalent) level, and the application of stress-factor reliability prediction techniques using detailed part failure rate data, such as are presented in Volume II of this notebook. In addition, this assessment should be supported by an evaluation of the results of any test that may have been performed on breadboard or prototype models that may have provided data relating to reliability factors.

c. <u>Reliability Input to First Article Configuration Inspection.</u> A third reliability engineering review point during the Acquisition Phase is the activity necessary to support the First Article Configuration Inspection (FACI). This final formal design review establishes the Product Configuration Baseline and permits the formal acceptance of the Part II Detail Specifications.

In general, the FACI concerns the comparison of the first article to be produced with the verified requirements of the Part II Detail Specification. These "build to" specifications do not contain defined reliability requirements. Therefore, a reliability design analysis is not required as a direct input to the FACI. In a typical system development program, the final verification of design reliability is performed in support of the CDR, and as a part of the Category I and Category II tests. In approving the design for production, it is assumed

that the required level of reliability, as verified by the CDR, will be achieved if the system meets the requirements of the Part II Detail Specifications.

Even though specific reliability design and testing requirements are not included in the Part II Detail Specifications, it is usually necessary to evaluate the design to verify the reliability design in areas that had previously been identified as high-risk areas and to assure that the required level of reliability is not being degraded due to differences between the specifications and the hardware produced, especially where design changes have been made to facilitate production.

6.2 Reliability Engineering In Support of Test and Evaluation.

Additional reliability engineering activities of the SPO during the Acquisition Phase include those performed in support of the Category I and Category II test programs. The contractor is normally responsible for planning, implementation, and subsequent follow-up activities in connection with these test programs. Also, the SPO activities concerned with monitoring and controlling the Category I and Category II test programs are the responsibility of the Deputy Director for Test and Deployment, and is not one of the defined engineering activities. However, the development of effective test programs demands the input of valid test objectives and other factors that are related to the engineering design characteristics of the system. Therefore, extensive engineering support is essential in establishing test objectives and acceptance criteria, defining environmental and operational test conditions, supporting test programs in progress, evaluating test data, and developing effective follow-up recommendations.

The reliability engineering activities associated with the overall engineering support of the test program are the responsibility of the contractor. To be effective, however, these activities must be fully monitored, coordinated, evaluated and controlled by the SPO. Therefore, the SPO reliability engineers must support the Deputy Director for Test and Deployment in areas outlined below. A detailed discussion of reliability testing is presented in Chapter 10.

a. Verifying reliability test objectives (e.g., desired and limiting MTBF requirements) for each CEI to be tested.

b. Determining the validity and practicability of consumer risk levels established for reliability testing.

c. Verifying the effectiveness of reliability test plans in relation to sampling, test duration, and accept/reject criteria.

d. Evaluating recommended test conditions, including environmental and operational factors.

e. Evaluating criteria such as definition of performance parameters to be measured during test, allowable degradation and definition of failure.

f. Monitoring tests in progress and resolving problems encountered that would effect the validity of the test.

g. Reviewing test reports to evaluate test results, identified problem areas, and recommended engineering solutions.

h. Advising the Program Director on the extent of any identified reliability engineering problems, on the selection of corrective action approach.

7. RELIABILITY ENGINEERING MANAGEMENT DURING THE OPERATIONAL PHASE

The Operational Phase of the system life cycle begins with the delivery and acceptance of the first item on contract, and continues until the final disposition of the last item. During this period, the system operation becomes the responsibility of the using command or activity, and the system engineering responsibility is transitioned from AFSC to AFLC. The change of reliability engineering responsibility as contract items are accepted by the using command is discussed in Chapter 3. Therefore, the specific reliability engineering activities as discussed here relate to either AFSC or AFLC engineering as appropriate.

Reliability engineering during the operational phase involves support of operational reliability test programs, providing reliability engineering input for modifications design and testing programs, and performing reliability engineering analyses and evaluation of field feedback data. These activities are summarized in Table IV-6, and are discussed in more detail in the following paragraphs.

7.1 Review of Category III Test Program Requirements.

This activity is discussed here even though the initial support activities by the SPO usually begin before the actual start of the Operational Phase. The Category III tests are performed by using command. However, the SPO and system contractor provide engineering support in the development of the test program plans and

Table IV-6. Reliability Engineering Activities-Operational Phase

Activity	Purpose	Input Data Source	Outputs	Where Used
. Review Category III Test Program Requirements.	. Assess Reliability Test plans for Category III testing.	. Initial Category III Test Program Plans. . Category I and II Reliability test reports. . Updated engineering documentation. . Updated system specifications. . Updated Part I Detail Specifications. . Engineering change proposals.	. Recommended revisions to, and/or comments relative to approval of Category III test procedures.	. Input to using command's Category III Test Program Plans and Procedures.
. Develop Follow-On System Modifications.	. Provide reliability engineering input to modifications.	. Category III Test Reports. . Updated Engineering Documentation. . Reliability Block Diagram and Model.	. Assessment of modification's impact on System Reliability. . Reliability Design requirements of modification.	. Modification Procurement Documentation. . Follow-on Development Test procedures.
. Define Follow-On Reliability Test Requirements.	. Provide reliability test requirements for test of Follow-On modification.	. Updated specifications. . Follow-On Test Program Plans . Reliability Design Requirements of Modifications.	. Recommended reliability test procedures and plans.	. Follow-On Development Test Procedures.

Table IV-6. Continued

Activity	Purpose	Input Data Source	Outputs	Where Used
. Field Feedback Data Analysis.	. Evaluate System Reliability during operation.	. Field Maintenance and Operational Data.	. Verification of Operational Reliability Achievement.	. Requirements for system modification. . Requirements for new systems. . Feedback to other Systems Development programs.

procedures. Such plans and procedures should be reviewed and evaluated by reliability engineering to assure adequate provisions for reliability testing.

The need for and extent of reliability testing during the Category III test will be determined based on the requirements of the using command, and the operational requirements imposed on the system. Also the results of previous reliability engineering efforts, and of the reliability testing during the Category I and Category II test programs should be taken into consideration in developing the reliability test procedures to be followed by the using command. Therefore, an important aspect of reliability engineering is the performance of a critical review of recommended Category III test procedures with the objectives of assuring an appropriate and effective reliability test. This review should include:

a. A review of previously identified high-risk areas, design change recommendations and actions, Category I and Category II test reports, and other documentation to identify specific needs for additional reliability testing.

b. A review of the operational policy and objectives of the using command.

c. A review of other tests to be performed during Category III testing to identify possible areas for reliability test consolidation.

d. A review of updated specifications, diagrams, and other engineering documentation to identify late changes in reliability requirements.

e. Consideration of time and cost constraints imposed on the Category III test programs and, from this, identification of limitations on reliability testing.

f. Review of instructions for conducting the reliability test, including sampling plan, test procedures, and acceptance procedures.

7.2 Development of Follow-On System Modifications.

Any follow-on modifications that are developed in response to findings of Category III or subsequent operational test programs should include reliability engineering as a part of the overall modification engineering effort. This should include a reliability engineering effort with objectives and activities similar to those of original

systems engineering program. The extent of this effort, however, is dependent on many factors, such as the complexity of the modification, and the degree to which the modification effects the system reliability.

7.3 Define Follow-On Reliability Test Requirements.

The effectiveness of follow-on modifications must be verified by means of follow-on testing of the modified system. Such testing is similar to Category I or Category II testing with the exception that the scope of testing is reduced to include only those tests necessary to verify the effectiveness of the modification. In general, such tests will include a minimum reliability testing effort to assure that system reliability has not been degraded. However, at times the reliability testing requires the full support of the SPO and contractor reliability engineering groups. Such extensive programs may be required in the event of modifications to alleviate a serious system reliability problem.

7.4 Field Feedback Data Analysis.

The analysis and evaluation of field feedback data is an area of reliability engineering activity that begins with the initial acceptance and operation of the system, and continues as long as there is a need for field failure and operational data. The characteristics of a field data collection and reporting system, are discussed in Chapter 7. Such a system provides the basic data input to the continuing reliability engineering efforts such as:

a. Identification of high failure rate equipment items.

b. Determining operational and environmental causes of failure.

c. Developing requirements for corrective action in the event of the identification of latent reliability problems.

d. Developing state-of-the-art reliability engineering data applicable to other system development programs.

8. RELIABILITY ENGINEERING ACTIVITIES DURING NON-SYSTEM PROCUREMENT PROGRAMS

Many of the reliability engineering activities discussed in preceding paragraphs, and most of the techniques described in subsequent chapters of this notebook are applicable to individual equipment procurement programs, even though extensive development effort is not required, and the defined life cycle phases are not identifiable. Quite often, for

example, a "non-system" program will involve the normal development and procurement of new equipment items for the operational inventory. In such cases, it is possible to identify stages of development that are similar to the system life cycle phases, although some system program activities may not be applicable, and others may be contracted or deleted in the interest of economy and expediency. Other procurement programs are less involved, and the reliability engineering activities are appropriately reduced in proportion to the overall engineering requirements.

In general, non-system procurement programs involve the design, production and testing of individual equipment items that may or may not be part of a defined system. In general, such programs can be classified as either (1) normal procurement, (2) development and experimental model procurement, (3) commercial equipment procurement, or (4) low value equipment procurement. The reliability engineering activities associated with non-system procurements can vary considerably, not only with respect to these different classes of procurement, but also with respect to individual procurement programs within a given class. However, certain basic reliability engineering activities are applicable to any procurement. Table IV-7 lists the more important reliability engineering activities normally associated with each general class of non-system procurement. The chapter references in the right hand column refer to subsequent chapters of this notebook that contain information relating to the particular activities. This list should not be considered as all-inclusive but can be used as a guide in establishing reliability engineering requirements for non-system programs.

Table IV-7. Reliability Engineering Activities During Non-System Programs

Type of Procurement	Purpose of Procurement	Typical Reliability Engineering Activities	References Chapters
Normal Procurement	- Service Test models	- Specify reliability requirements for equipment design and development.	6, 8, 10
	- Pre-production models	- Develop reliability block diagrams and mathematical models.	8, 9, 11
	- Development models	- Perform reliability predictions, FMEA and trade-off studies as required.	9, 11
	- Individual equipment for operational use	- Analyze equipment reliability engineering requirements, perform stress analyses, and participate in end item and part selection activities.	6, 11
		- Develop reliability test requirements and support development of reliability test plans and procedures.	10
		- Analyze reliability test and field data and develop design changes for reliability improvement.	7, 11

Table IV-7. (Cont'd)

Type of Procurement	Purpose of Procurement	Typical Reliability Engineering Activities	References Chapters
Development and Experimental Model Procurement	- Advanced development models	- Specify reliability requirements for equipment design.	6, 8
	- Experimental models	- Perform reliability prediction and analysis.	9
	- Other models not intended for operational use	- Design and perform reliability tests.	10
		- Analyze test data, perform failure mode and effects analyses, etc.	11
		- Make recommendations for reliability improvement in future designs.	11
Commercial Equipment Procurement	- Commercial and other "off-the-shelf" equipments procurred for limited operational use	- Specify reliability requirements for procurement specifications.	6, 3, 10
		- Define reliability test requirements.	10
		- Support development of reliability acceptance test plans and procedures.	10
		- Evaluate contractor's service and life test reliability data.	6

Table IV-7. (Cont'd)

Type of Procurement	Purpose of Procurement	Typical Reliability Engineering Activities	References Chapters
Low Value Equipment Procurement	- Low value items procurred for limited and non-critical operational use	- Specify reliability requirements for procurement specifications.	6, 10
		- Design reliability test plans and procedures.	10
		- Perform tests and evaluate reliability test data.	10

CHAPTER 5

RELIABILITY PROGRAM DATA

1. AIR FORCE SYSTEM DEVELOPMENT DATA REQUIREMENTS

The formal methodology instituted by the Air Force for managing complex system development programs includes five major areas of management activity: procurement and production; program control; configuration control; system engineering; and test and deployment. Effective coordination of all areas of management requires a uniform system for controlling the acquisition and distribution of management, scientific, engineering, and logistics information, reports and documentation. Such "data", which are essential to the management of a system development program, are managed in accordance with a standardized procedure as required by AFR 310-1, and implemented by AFSCM/AFLCM 310-1.

Air Force Regulation AFR 310-1 establishes official Air Force policy concerning the identification, justification, selection, acquisition, and control of all data relevant to system development.

In response to the requirements of AFR 310-1, AFSC requires details of system development programs to be documented and reported by means of a strictly controlled series of recurring and non-recurring reports and other forms of documentation. This data acquisition program is managed in accordance with AFSCM/AFLCM 310-1, "Management of Contractor Data and Reports," which prescribes data management procedures, and includes the Authorized Data List (Volume II of AFSCM/AFLCM 310-1). This list specifies the content and format of approximately 340 standardized "Data Items" that have been approved for use on AFSC development contracts. These Data Items have some application during essentially all phases of the system life cycle, but are primarily concerned with the definition and acquisition phases when contractor activities are most significant.

1.1 Reliability Data Requirements in System Development Programs

Many of the Data Items specified in AFSCM/AFLCM 310-1 are intended for the direct support of the reliability program. Other Data Items, which are intended to support other activities of the system development program, also require certain types of reliability data that are essential to other aspects of the system development program.

The Authorized Data List is universal in scope, and contains data items applicable to a variety of development programs. Therefore,

a certain degree of selectivity is essential in establishing reliability data requirements for specific system development programs. It is, therefore, the intent of this chapter to provide a guide for the selection of reliability data requirements for application to a system development program, and for the management of these data during the conceptual, definition and acquisition phases of the system life cycle. This includes consideration of certain data items not specifically identified in the "reliability" category, but which require specific reliability data inputs, or which may otherwise impact on the reliability program.

1.2 Reliability Data Requirements of Non-System Programs

The data management procedures specified in AFSCM/AFLCM 310-1 are based on the requirements of system development programs that are managed in accordance with AFSCM 375-4. However, many of the data items in the Authorized Data List are also applicable to the procurement of individual equipment items, experimental or developmental models, commercial items, or other types of procurement not warranting a formal system program approach. For example, a program for the procurement of an individual equipment, and which involves development and design engineering and analysis tasks, will require essentially the same types of reliability data as a system development program, even though the AFSCM 375 series documents are not imposed. The extent of the data requirements for non-system programs will vary depending on the type of procurement, the amount of engineering required, and the importance of reliability in relation to the intended use of the equipment. Even the least demanding programs will require reliability specification and acceptance test requirements data to assure the procurement of appropriately reliable items.

In most cases the reliability program data can be obtained by selective application of data items from the Authorized Data List. However, due to the economic considerations associated with most non-system procurements, the reliability data requirements should be limited to those that are essential to the particular program. In view of this, a brief discussion and guide for the selection and application of AFSCM/AFLCM 310-1 data items to a variety of non-system procurement programs is included in the latter portions of this chapter.

2. RELIABILITY DATA REQUIREMENTS IN AFSCM/AFLCM 310-1

The Authorized Data List (Volume II of AFSCM/AFLCM 310-1) contains the approved AFSC/AFLC Form 9, or "Data Items," which are authorized for possible use on system development contracts. Each Data Item has been assigned to one of thirteen functional categories depending on the most common use of the particular data.

The functional categories that are of major interest to reliability program management are:

Category C - Configuration Management

Category R - Reliability/Maintainability

Category S - System/Subsystem Analysis

Category T - Test

Other functional categories also contain data items that are indirectly related to the reliability program. However, any such reliability data requirements are generally derived from the data included in the four categories mentioned above. Therefore, appropriate management of these major data items will assure the acquisition of essential reliability data for use in connection with other areas of management.

Category R contains the Reliability/Maintainability Data Items and, therefore, contains those data items that most directly concern the reliability program. Category R includes fifteen data items. Eight of these are specifically related to activities of the reliability program, while two others, which are more general in nature, concern both the reliability and maintainability program. The relationship of these data items to the reliability program is apparent.

The remaining four Category R data items, which are specifically addressed to the activities of the maintainability program, also contain requirements that directly or indirectly impact on the reliability program. For example, certain reliability data are essential in developing inputs to the maintainability data items. Therefore, in selecting reliability data items for application to a particular contract, consideration should also be given to the data requirements of the maintainability program.

The specific reliability data requirements of data items list in Functional Categories C, R, S and T are summarized in Table V-1. This table identifies specific data items by number and title, and briefly summarizes the reliability data requirements of each. Unless otherwise indicated, the references in the right-hand column refer to specific paragraphs of the data item under consideration.

Table V-1 Reliability Data Requirements

Functional Category C - Configuration Management			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
C-1-35.1-1	System Performance/Design Requirements General Specification	a. Reliability Requirements - Quantitative system reliability requirements - Conditions under which requirements are to be met - Reliability apportionment model	Paragraph 3.1.3.1 of Example "A" (See Paragraph 3.1.3.1 of AFSCM 375-1 Exhibit I)
		b. Reliability Testing - Requirements for reliability testing at various levels of system assembly - Requirements for recording Cat. I and Cat. II Reliability Data	Paragraph 4.1.3 of "Sample Format" (See Paragraph 4.1.3 of AFSCM 375-1, Exhibit I)
C-2-46.0-1	Contract End Item Detail Specification (Prime Equipment) - Part I	a. Reliability Requirements - Quantitative CEI reliability requirements - Definition of success or failure at stated confidence levels - Time period necessary for reliability demonstration	Paragraph 3.1.2.1 Sample Format "B" (See Paragraph 3.1.2.1 of AFSCM 375-1, Exhibit II)
		b. Reliability Test and Analysis Requirements - Requirements for analysis to verify compliance with specified reliability - Data sources, volume of data, assumptions - Requirements for testing solely for requiring reliability data	Paragraph 4.1.4 of Sample Format "B" (See Paragraph 4.1.4 of AFSCM 375-1, Exhibit II)

Table V-1 Continued

Functional Category R - Reliability/ Maintainability			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
R-101	Reliability Program Plan	- R Management and Personnel Organization - Policy and action responsibilities and functions of R organization - Description of failure Reporting scheme, feedback corrective action - Plan to demonstrate achieved R - Description of contractor methodology for R calculation	Entire Data Item
R-102	Maintainability Program Plan	- Plans for providing reliability data input to maintainability predictions - Interface with reliability program	Paragraph 3h. Paragraph 4b.
R-103	Reliability/Maintainability Allocations, Assessments, and Analysis Report	- R/M Models - System/Equipment breakdown - Failure mode and effects analysis - Description of trade-offs Studies - Effects of storage, shelf life, handling, etc. - R/M allocations tabulation and analysis	Entire Data Item
R-104	Defective or Inadequate Parts/Specifications Notification (Emergency)	- Various detailed parts data and nomenclature	Entire Data Item
R-105	Failure Summary Reports	- Failure report data for procuring activity and RADC Reliability Central - Types, severity, and relative frequency of failure	Entire Data Item

Table V-1 Continued

Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
Functional Category R- Reliability/Maintainability (Continued)			
R-106	Reliability Test and Evaluation Plan	- Test objectives - Test equipment - Data required - Test plan - Environmental conditions - Test facilities	Entire Data Item
R-107	Maintainability Demonstration Plan	- Source of reliability (failure rate) data for input to maintainability demonstration plan	Paragraph e.(11) (See Appendix A of MIL-STD-471)
R-108	Reliability and Maintainability Data Reporting and Feedback	- Provides guidelines for the preparation of AFSC 258/258-4 Maintenance Discrepancy/Production Credit Record - Description of data items - Definition of terms - Reporting formats	Entire Data Item
R-109	Computer Programmed Mathematical Model for Reliability	- Model must have capability to predict system and subsystem performance and update performance estimates based on Cat. I and Cat. II tests - Programmed in FORTRAN	Entire Data Item

Table V-1 Continued

Functional Category R - Reliability/Maintainability (Continued)			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
R-110	Reliability Program Status Report	- An accounting of work done and results obtained on each task defined by the work statement - Status of unresolved problems - Status of each unresolved design review action - Status of attainment	Entire Data Item
R-111	Maintainability Program Status Report	- Updated reliability predictions as necessary for developing maintainability prediction trends	Paragraph 3.
R-112	Reliability Test and Evaluation Reports	- Prepared according to MIL-STD-831 - Identify test article - Methods and conditions of demonstration, data evaluation - Results - Confidence intervals - Anticipated corrective action - Test conclusions and recommendations	Entire Data Item
R-113	Maintainability Demonstration Reports	- Should be generally compatible with the Reliability Test and Evaluation Report (Data Item R-112)	

Table V - Continued

Functional Category R - Reliability/Maintainability (Continued)			
Data Item	Title	Reliability Data Requirements	[illegible]
R-114	Reliability Analysis for Exploratory, Advanced Development Models	- In accordance with MIL-STD-756A - System description - R model description - Stress levels - Computed R - Recommendations	Entire Data Item
R-115	Reliability, Commercial Equipment	- Service and life-test reliability data on designated equipments - Exact data is a discretion of contractor subject to MIL Spec requirements	Entire Data Item

Table V-1 Continued

Functional Category S - System/Subsystems Analysis			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
S-1-6.0	System Analysis Summary Report	- Interrelationship between subsystems and reliability, and the relation of each to total system and mission requirements - Use effectiveness model as basis - Reflects integration system reliability	
S-5-14.0	Technical Proposal	- Description of Bidder's ability to provide required reliability - Estimate of maximum stress levels - Estimate of achievable reliability - Anticipated reliability problem areas - Proposed reliability demonstration procedures - Reliability values in system effectiveness model - GFE problem areas - Proposed reliability program and organization	Paragraph C3
S-10-14.0	Proposal - Flight Control Subsystem	- Predicted reliability of proposed design - Data source and analytical approach used in prediction - Proposed reliability test program - Preliminary failure analysis	Paragraph (10) Paragraph (11)
S-12-14.0	Proposal - Reconnaissance Subsystem	- Predicted reliability of proposed design - Data source and analytical approach used in prediction - Proposed reliability test program	Paragraph (16)

Table V-1 Continued

Functional Category S - System/Subsystem Analysis (Continued)			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
S-13-14.0	Proposal - Environmental Control and Protection Subsystem	- Predicted reliability of proposed subsystem - Planned reliability program	
S-15-14.0	Proposal - Guidance Subsystem	- Predicted reliability of proposed design - Data source and analytical approach used in prediction - Comparison of predicted reliability with required reliability - Proposed reliability test program	Paragraph 3
S-16-14.0	Proposal - Flight Test Vehicle Power Subsystem	- Predicted reliability of proposed design - Proposed reliability test program	Paragraph A(6), B(6), and C(2)
S-53-6.1	Requirements Allocation Sheet	- Design requirements for reliability	Paragraph 1C(4)
S-54-6.1	System/Design Trade Study Reports	- Predicted impact of alternate design approaches on reliability - Reliability factors included in comparison matrix - Reliability data in support of design selection	Paragraph 3 Paragraph 4 Paragraph 5

Table V-1 Continued

Functional Category S - System/Subsystem Analysis (Continued)			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
S-57-6.1	Design Sheets (Not used when C-2-46.0-1 is required	a. Reliability Requirement - Quantitative reliability requirements - Definition of success or failure at stated confidence level - Time period necessary for reliability demonstration	Paragraph 3.1.2.1
		b. Category 1 Reliability Test and Analysis - Testing specifically for reliability - Data sources, volume of data, assumptions - Requirements for analysis to verify compliance with specified reliability	Paragraph 4.1d and 4.1.4
S-60-18-0	Maintenance Loading Sheets	- Failure rate data for "frequency of function" for corrective maintenance	Paragraph 1.g.

Table V-1 Continued

Functional Category T - Test			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
T-101	System Test Plan	- Reliability testing requirements in relation to outline of total system test program - Reliability tests on CEI during Category I testing - Reliability tests on system during Category II testing - Reliability testing (if any) during site activation - Reliability test program requirements with regard to: - Organizational responsibilities - Milestone and schedules - Test objectives - Test support requirements - Test methods and planning	Entire Data Item
T-102	Category I Test Plan/Procedures	- Reliability test planning information (during definition phase) - Reliability test procedures (during acquisition phase) (This plan recognizes reliability test and analysis as one of four major functional test categories)	Paragraph 3a. Paragraph 3b.

Table V-1 Continued

Functional Category T - Test (Continued)			
Data Item	Title	Reliability Data Requirements	Applicable Data Item Paragraph No., etc.
T-106	Category II Test Plan/Procedures	- Reliability test plan as part of overall category II test plan, defining the following: - Reliability as a test item - Reliability participation in test organization - Milestone and schedules for reliability testing - Reliability test support requirements - Objectives or reliability testing - Reliability test environment - Reliability test procedures - Reliability data collection and analysis (This plan recognizes reliability and maintainability evaluation as one of the specific items to be included in an outline of test methods and procedures)	Entire Data Item
T-107	General Test Plan (Equipment)	- Reliability test plan and procedure information as appropriate (This is a general-purpose Data Item to define testing requirements when Category I or II testing is not applicable)	Entire Data Item

Table [illegible] Continued

Functional Category T - Test (Continued)			
Data Item	**Title**	**Reliability Data Requirements**	**Applicable Data Item Paragraph No., etc.**
T-109	Qualification Test Plan (Equipment)	- Reliability testing requirements as appropriate during qualification testing (This is primarily intended for non-system, R&D, or other procurements not in accordance with the uniform specification program)	Paragraph 1 e (6)
T-117	Category I Final Test Report	- Reports on results of reliability test and analysis performed as part of Category I testing - Objectives or reliability tests - Test results - Summary of reliability test data analysis - Conclusion - Findings - Recommendations	Entire Data Item
T-120	Category II Test Report	- Report on results of Category II reliability Testing - Comparison between planned objectives and test results - Identification of test results that differ from objective - Identification of planned tests for which results were not obtained - Summary of total system reliability, including confidence factors - Trade-off recommendations between reliability, maintainability and system operational effectiveness.	Paragraph 1c Paragraph 2h

3. RELIABILITY DATA REQUIREMENTS CITED IN CONTRACTS DURING THE SYSTEM LIFE CYCLE

The reliability data requirements as specified in AFSCM/AFLCM 310-1 are used as required throughout the Definition and Acquisition phase of system development and during equivalent stages of non-system development (see Chapters 3 and 4).

Certain reliability data are also obtained during the Development and Transition stages of the Conceptual phase before the SPO is established. Some of these data can be obtained via standardized data items. However, most of the reliability data generated during the Conceptual phase are applied to the development of the PTDP, and are developed by Air Force rather than contractor activities.

Additional reliability data are obtained during the Operational phase of the system life cycle. However, most of these data are in the form of empirical operational and failure data, and are obtained via the Air Force Maintenance Data Collection System as discussed in Chapter 7.

Reliability data requirements commonly encountered during the Conceptual, Definition, and Acquisition phases, and which are obtained via the standardized Data Items of AFSCM/AFLCM 310-1, are summarized by phase in Table V-2. Additional reliability program data generated during the Conceptual phase are reviewed in Paragraph 4 of this chapter.

4. AIR FORCE - GENERATED RELIABILITY DATA

In general, reliability data acquired from contractors during the system life cycle will be limited to the type indicated in Paragraph 3. However, before these data can be developed, certain reliability data must be generated by the Air Force. Such data are typically developed during the conceptual phase in preparing for Transition to the Definition Phase activities, and during Phase A of the Definition Phase. Thereafter, reliability data development will become the responsibility of the contractor.

Based on knowledge gained from the early development and system study activities of the conceptual phase, Headquarters USAF issues the SOR/OSR/ADO documents which establish fundamental system requirements. These documents provide the basis for the subsequent development of more detailed reliability data. Typical information from which subsequent reliability data are developed include:

Table V-2 Data Item Applicability

Data Item Number	LIFE CYCLE PHASE						
	CONCEPTUAL			DEFINITION		ACQUISITION	
	Exploratory Development	Advanced Development	Conceptual Transition	Phase A	Phase B	Development	Production
C-1			X	X	X		
C-2					X	X	
R-101					X		
R-102					X		
R-103						X	
R-104						X	
R-105						X	
R-106					X		
R-107					X		
R-108						X	
R-109	X	X	X	X	X	X	
R-110						X	
R-111						X	
R-112						X	
R-113						X	
R-114	X	X					
R-115					X	X	
S-1					X	X	
S-5				X	X		
S-10					X		
S-12					X		
S-13					X		
S-15					X		
S-16					X		
S-53						X	
S-54						X	
S-57						X	
S-60						X	
T-101				X	X		
T-102						X	

Table V-2 (Cont'd)

Data Item Number	LIFE CYCLE PHASE						
	CONCEPTUAL			DEFINITION		ACQUISITION	
	Exploratory Development	Advanced Development	Conceptual Transition	Phase A	Phase B	Development	Production
T-106						X	
T-107						X	
T-109						X	
T-117						X	X
T-120						X	X

(1) Basic system functional structure and time relationships.

(2) Basic reliability and maintainability allocations.

(3) Reliability block diagrams.

(4) Estimates of allowable in-commission rates, downtime allocations, manpower, and available maintenance resources.

4.1 Reliability-Related Input to the PTDP

In response to the SOR/OSR/ADO, the Air Force project management develops the Preliminary Technical Development Plan (PTDP), which defines the technical portion of the Program Requirements Baseline governing the activities of the Definition Phase. The reliability data, and supporting information included in the PTDP will provide the reliability requirements for the initial system specification. Therefore, in the development of the PTDP, the Air Force should assure that the following types of information and data are included:

(1) Planned system functional description, including:

- Functional diagrams
- Engineering descriptions of the functions
- Established system design requirements
- Gross solutions to these requirements
- Predicted equipment configuration
- Trade-offs considered and areas requiring further exploration (high risk technical, cost, or schedule areas)

(2) Preliminary operation plans, including:

- Mission duration requirement for each type of mission
- Reaction time, availability, and ready rates required
- Planned utilization rates of system elements

(3) Plans for a reliability program outlining how reliability requirements will be achieved, providing for:

- Overall mission reliability for each type of mission
- Reliability after storage goals; other measures as required
- Reliability apportionment, prediction, and modeling
- Determination of equipment environmental conditions
- Periodic specification review (when, how often, etc.)
- Reliability participation in System Engineering Design Reviews
- Coordination with human error analysis and prediction
- Reliability tests, demonstration, and resolution of problem areas
- Malfunction and failure reporting and analysis
- Planned products, milestones, and schedules

4.2 Reliability Input for the Initial General Specification

The most significant reliability data to be developed by the SPO during Phase A of the Definition Phase is the reliability requirement and corresponding reliability assurance provisions for the initial System Performance/Design Requirements General Specification. This specification is developed following Exhibit I of AFSCM 375-1. (Subsequent generations of the General Specification will be developed by the contractor in accordance with Data Item C-1-35.1-1 of AFSCM/AFSLM 310-1, as discussed in Paragraph 3.) The system reliability data included in the General Specification includes:

(1) System reliability requirements stated in quantitative terms

(2) Conditions under which requirements are to be met

(3) Reliability apportionment model (when appropriate) allocating reliability to system segments

(4) Reliability testing requirements at various levels of system assembly

(5) Reliability test data recording requirements as applicable during Category I and II testing.

5. RELIABILITY DATA REQUIREMENTS FOR NON-SYSTEM PROGRAMS

The reliability data requirements, as discussed in preceding paragraphs, are based on specific Data Items listed in AFSCM/AFLCM 310-1, and on certain configuration management requirements of AFSCM 375-1. These documents are based on large system acquisition programs wherein specific life cycle phases can be defined. Quite often, the data requirements of non-system programs are similar to those of a system program, even though specific program phases may not be defined. However, the degree of detail and complexity of data requirements applicable to large systems is not always necessary in many small scale programs. For example, procurement of individual "off-the-shelf" equipments, and other such equipment items, may not warrant a full-scale data management program. This is true of reliability data as well as other categories of data normally obtained during system development.

5.1 Typical Non-System Reliability Data Requirements

Even though extensive reliability data are not always required on such programs, there is still a need for a minimum amount of data to specify a reliability requirement, and to assure that appropriately reliable items are being procurred. Typical reliability data requirements for several categories of non-system procurements are described below.

a. <u>Normal Procurements</u>. Service Test, Preproduction and Development Models, and individual equipments procurred for operational use.

(1) Mean Time Between Failures (MTBF), requirements and failure definition

(2) Useful Life Requirements

(3) Test Requirements - Reliability Demonstration

- Definition of test plan and test level and applicable MIL Specification

- Justification for chosen test plan and test level

- Test time and definition of allowable failures and level of confidence

(4) Production reliability test plan (where applicable)

b. <u>Advanced Development and Experimental Models not Procurred for Operational Use.</u>

(1) Functional diagrams

(2) Parts count

(3) Description of stress analysis

(4) Description of modeling tools

(5) Computed reliability parameters

(6) Reliability demonstration requirements

c. <u>Commercial "Off-the-Shelf" Equipment.</u>

(1) Mean time between failure requirements, and failure definition

(2) Reliability assessment report

(3) Historical reliability data

d. <u>Low Value Items for Non-Critical Use.</u>

(1) MTBF requirements and failure definition

(2) Reliability demonstration requirements:

- Test Plan
- Test Time
- Maximum allowable failures

5.2 AFSCM/AFLCM 310-1 Data Items Applicable to Non-System Procurements

Many of the data items identified and described in Paragraph 2 of this chapter are applicable for acquiring reliability data for many non-system procurement programs. In general, the particular data items used must be selected according to the particular requirements of the program under consideration. In most cases, however, the

reliability data requirements will be satisfied by selecting data items as indicated in Table V-3. In any case, the specific data items selected should be reviewed and revised where necessary to assure that all essential data are being obtained, and to delete any unnecessary data requirements.

Table V-3 Data Items Applicable to Non-System Procurement Programs

Data Item Number	Procurement Category (See Paragraph 5.1)			
	Normal Procurement	Development Experimental	Commercial "Off-Shelf"	Low Value
R-101	✓			
R-102	✓			
R-103	✓ *		✓ *	
R-104	✓		✓	✓
R-105	✓			
R-106	✓		✓	✓
R-107	✓			
R-108	✓			
R-109	✓ *			
R-110	✓			
R-111	✓			
R-112	✓			✓
R-113	✓			
R-114		✓		
R-115			✓	

* Applicable only in procurement of large, complex equipment items.

CHAPTER 6

ASSURING RELIABILITY PROGRAM EFFECTIVENESS

1. INTRODUCTION

Reliability requirements have become a major element in planning, developing, designing, engineering, producing and purchasing military equipments and systems. As with other performance characteristics, such as range and power output, for which requirements are established, it is important to recognize those efforts and activities which must be undertaken before the final product is tested and delivered in order to have some assurance that performance objectives will be met. For instance, before hardware is fabricated it is normal to spend time and effort (often considerable time and effort) in the "paper design" stage, during which extensive calculations are made to "show" that the design (which includes many factors, such as components, structural relationships, and expected values) will meet required performance objectives. Stages which follow the paper design are usually undertaken only after there is some assurance (either through calculations, review, comparisons, simulation or some combination of all of these) that the design will meet required performance objectives. Each progressive stage through complete fabrication is undertaken only after results have been developed which provide a reasonable degree of assurance that the outcome will be successful. Finally the product (i. e., component, equipment, or system) will be produced and delivered only after tests show that objectives or requirements for performance characteristics will be met.

This same general pattern of programmed or planned activities such as review through test is also appropriate for providing assurance that the final product will be delivered with the required reliability. That is, it is appropriate to think in terms of a reliability program as a means of ensuring that reliability requirements/objectives will be met. The purpose of the reliability program would be to: (1) plan for the appropriate reliability oriented activities, including establishing reliability requirements; (2) ensure that these activities are being carried out; (3) monitor and evaluate results; (4) ensure that there are sufficient controls to prevent implementing succeeding stages without having successfully completed preceding stages; and (5) ensure that meaningful criteria have been established and are being used as the basis for decisions concerning acceptability or non-acceptability of results.

2. RELIABILITY PROGRAM RESPONSIBILITIES

In general, the assurance of meeting reliability requirements and assuring reliability program effectiveness is a responsibility which must be undertaken by the System Project Office (SPO) and the hardware contractor.

Contractor responsibility is oriented toward responding to the quantitative reliability requirements and providing the organization and functional resources and control which will provide the assurance that the reliability program will be effective and that reliability objectives will be met.

From the System Project Office (SPO) or program manager point of view, there are three areas of general concern. First, there is the concern over the reliability requirements as a performance characteristic. That is, the SPO or project manager responsibility includes the requirement to know what is desired in the way of reliability requirements and to express these in a meaningful way to hardware contractors. Second, there is concern over what constitutes an effective reliability program consistent with established quantitative requirements as a performance characteristic. That is, what are the elements of a sound reliability program, including contractor organizational structure and levels of responsibility. Third, there is concern over the methods or techniques which should be used to assure the effectiveness of a reliability program. That is, what are the criteria for acceptance and what are the means for conducting effective monitoring and evaluation of performance.

Major elements impacting on reliability program effectiveness can be described as falling into five areas: (1) reliability specification; (2) planned reliability activities, such as design review and testing; (3) evaluation of reliability plans and organizational structure; (4) preparation of criteria to be used as a basis for conducting evaluation; and (5) establishing communication links to ensure rapid response both to problem areas and to acceptable results.

Air Force documents provide the SPO and project managers with the means for imposing general reliability program requirements and acquiring appropriate information from the contractor. In particular, AFSCM/AFLCM 310-1 provides the basis for imposing reliability program and documentation requirements and the AFSCM 375 series provides useful information concerning definitions and general guidelines. The purpose of this chapter is to provide an overview of the information contained in these documents and to provide information which would lead to more effective utilization of means for assuring reliability program effectiveness.

3. SPECIFYING RELIABILITY REQUIREMENTS

Specifying reliability requirements is one of the key SPO responsibilities and probably one of the first elements which should be considered in establishing the need for a reliability program. Reliability requirements generally consist of two distinct segments. First there is the segment of the reliability requirement which is performance oriented. It is extremely important that this segment of the reliability requirement be expressed quantitatively in a manner (i. e., using the reliability definition, measure, or unit) which is consistent with mission or tactical objectives. Second, there is the segment of the reliability requirement which is activity, data, test, or "program" oriented. This segment of the requirement also must be quantitative where possible (the test requirement, for example) and it must impose only those activities and data deliverables which are consistent with the type hardware program and the quantitative reliability requirements.

From AFSCM 375-3, (15 June 1964 issue, paragraph 33, page 44) reliability is defined as the probability that a system will perform its designated mission for the specified length of time in the operational environment. The resultant reliability in its broadest sense is a measure of how well everyone has done his job. It is the result of many interplaying factors, many of which are engineering responsibilities (see AFSCR 80-1). This is a standard definition; however, there are other measures of reliability such as Mean Time Between Failure (MTBF), Failure Rate, and Mean Time Before Maintenance (MTBM). These latter reliability measures are often more directly useable as design criterion and therefore the application of these measures is often the basis for communication between engineers. In any event, the SPO or project manager has the responsibility for ensuring that the reliability requirement is expressed in quantitative terms. Policy concerning quantitative reliability requirements is established in AFR 80-5 and AFSCR 80-1. Quantitative reliability requirements provide performance parameters which must be specified, designed to, and measured. This quantification process is basic to achieving the reliability desired in modern systems.

In addition, the SPO or project manager has the responsibility for imposing reliability program requirements and test requirements. MIL-R-27542 (Reliability Program for Systems, Subsystems, and Equipment) establishes requirements for a comprehensive reliability program. This specification is suitable as a contractual call-out for full compliance. However, if the peculiarities of a program indicate that deviations would be in the best interests of the Air Force, such deviations should be carefully defined and negotiated with the contractor prior to entering into an Acquisition Phase contract. MIL-R-27542 elaborates on various elements of a reliability program such as reliability requirements, reliability

apportionment, reliability estimates, design reviews, failure data collection, analysis, corrective action, and reliability demonstrations on or before specified program milestones.

In establishing test requirements, for example, experience has shown that for systems with very high reliability requirements, a production reliability testing program is essential. Such a program normally provides random selection of production-run equipment for specific reliability testing. In some cases complete testing may be justified, but generally equipment will be tested for critical weakness, electromagnetic interference effects, margins of safety, and reliability data.

As mentioned above, reliability requirements and particularly reliability performance requirements should be quantitatively expressed whenever possible and the unit of measure used should be consistent with intended use and operational/tactical objectives. For instance, the units such as "probability of survival for a given mission time" may not be appropriate for a communications system which is expected to operate continuously. In the case of a communications system the probability that a given number of channels is "up" at any one time or a mean time between failure (in hours) for each channel may be more meaningful. In addition a reliability requirement for meeting a given probability of mission completion should include confidence bounds in order to provide a basis for a meaningful evaluation. A reliability requirement in the form of a probability of mission completion with appropriate confidence bounds is more meaningful and results in a more complete reliability statement based on test or demonstration data. It should be noted, however, that before a confidence bounds statement (i. e., requirement) can be established or developed from data, equipment/system failure characteristics or distribution (e. g., exponential, Weibull, gamma) must be known or assumed. An erroneous assumption concerning the appropriate distribution could lead to a wide disparity between expected and actual reliability performance on an equipment or system which passed acceptance criteria based on an assumed failure characteristic. See Chapter 10, Reliability Measurement for a more comprehensive presentation on measuring reliability.

Alternative mission requirements and the correspondingly most appropriate means for expressing reliability together with the underlying technical details related to various possible failure characteristics or distributions are far too lengthy to be included here. However, there are guidelines which the SPO or project manager can follow in determining how the quantitative reliability performance requirement should be expressed. Guidelines which are presented in Table 6-1 are based on the following four basic ways in which a reliability requirement can be expressed.

(1) As a mean-time-between-failure, MTBF. This definition is useful for long-life systems in which the form of the reliability distribution

is not too critical, or where the planned mission lengths are always short relative to the specified mean life. This definition is appropriate for specifying mean life, however, equipment behavior in early life may not be the specified level of reliability, because early failures due to design "bugs" may initially distort the true system behavior.

(2) As a probability of survival for a specified period of time, t. This definition is useful for defining reliability when a high reliability is required during the mission period, but mean-time-to-failure beyond the mission period is of little tactical consequence except as it influences availability.

(3) As a probability of success, independent of time. This definition is useful for specifying the reliability of one-shot devices and those which are cyclic, such as the flight reliability of missiles, the launch reliability of launchers, or the detonation reliability of warheads.

(4) As a "failure rate" over a specified period of time. This definition is useful for specifying the reliability of parts, components, and modules whose mean lives are too long to be meaningful, or whose reliability for the time period of interest approaches unity.

4. RELIABILITY DESIGN REVIEWS

Once a reliability requirement has been developed, some means must be established for monitoring progress toward meeting this requirement and for monitoring contractor performance to ensure that reliability oriented activities as required and proposed have been implemented and are being effectively carried out. One means of accomplishing this monitoring is through formally held and/or documented design reviews either as part of engineering reviews which include reliability or through reviews which are held specifically for reliability.

In general, engineering design reviews and evaluations should include reliability as a tangible operational characteristic of the system, equipment, assembly, or circuit under review. Reliability considerations during the design reviews should include:

(1) Performance requirements and definitions of failure (e. g., tolerances, wear, and parameter shifts).

(2) The apportionment/modeling techniques used to establish the reliability design goals for sub-units which will ensure that the reliability specified for units will be met.

CONDITIONS OF USE / LEVEL OF COMPLEXITY	Continuous Duty Long Life (Repairable)	Intermittent Duty Short Missions (Repairable)	Continuous or Intermittent (Non-Repairable)	One-Shot (Time-Independent)
Complex Systems (Larger than 500 Active Element Groups*)	R(t) or MTBF	R(t) or MTBF	R(t)	P(S)
Systems Subsystems Equipments (Less than 500 Active Element Groups)	R(t) or MTBF	R(t) or MTBF	R(t) or λ	P(S) or P(F)
Modules Components Parts (10 Active Element Groups or less)	λ	λ	λ	P(F)

Code:

R(t) = Reliability for specified mission, or period of time, t.
MTBF = Mean-time-between-failures, or mean life.
P(S) = Probability of success.
P(F) = Probability of failure.
λ = Failure rate.

Figure 6-1. Guidelines for Expressing Reliability

*An Active Element Group (AEG) is the smallest practical functional building block which could be economically considered and which would not be specifically related to existing configurations.

(3) A reliability prediction of the current design, supported by detailed calculations and data sources.

(4) Failure mode analysis of the design with particular emphasis upon the reduction of marginal failure modes which are difficult to isolate and repair.

(5) Evaluation of trade-offs between performance, maintainability, weight, space, power, cost, and time factors made for design optimization.

(6) Environments to which the device, item, or circuits will be subjected in the use configuration, including storage, transport, and production process environments.

(7) Planned tests and/or the results of all tests conducted to date.

(8) Plans for reliability improvement and problem solutions.

In addition, reviews should include an evaluation of the contractor's reliability program from a functional/organizational, reporting, control, and task point of view. That is, the review should be used as a means for monitoring reliability "progress" with respect to the complete reliability requirement, quantitative as well as qualitative. Thus a description of the organization and personnel responsible for reliability, the tasks being conducted or completed, and the reporting/sign-off structure would provide an indication of the degree to which reliability is being monitored and controlled within the contractor's organization. This process of evaluating reliability design progress as well as reliability program implementation could be a very useful means of assuring reliability program effectiveness.

The detail to which early reliability design review is conducted, whether as a separate effort or as part of regular engineering design reviews is a function of the point in the cycle at which such reviews are conducted. Even if reliability design reviews are to be conducted separate from engineering reviews, it is essential that close coordination be maintained. Such coordination is necessary primarily because engineering reviews such as Systems Design Review (SDR), Preliminary Design Review (PDR) Critical Design Review (CDR), and First Article Configuration Inspections (FACI), as detailed in various Air Force Documents such as AFSCM 375-5 and ESDP 375-10 are conducted with specific objectives and the results of these reviews are used as the basis for decisions such as those concerning continuation, changes, and acceptability. The context of reliability reviews conducted separately from engineering reviews should follow the broad outline presented in the documents mentioned above with one possible exception. Where possible the acceptance of resultant designs from a reliability point of view should be made in bulk (that is at large component, functional, or equipment level) rather than on the basis of

individual design packages. Evaluation and acceptance in bulk provides a much better opportunity for making trade-offs and determining whether reliability on some packages can be relaxed (with attendant cost/schedule savings) because other packages within a functional unit have been designed at a higher than anticipated level of reliability.

Detailed direction and guidance for conducting SDR's, PDR's, CDR's and FACI's are presented in ESDP 375-10 (Instructions For Conducting Formal Technical Reviews, Inspections, and Demonstrations); AFSCM 375 series including AFSC 375-1, Exhibits I, II, and XIV and AFSCM 375-5; and AFR80-28(Engineering Inspections).

These documents present review requirements pertinent to characteristics, in general, other than reliability. However, reliability performance and program requirements can be made a part of the criteria for acceptability. Whether integrated with engineering reviews or conducted separately (but in coordination with engineering reviews) it should be understood that the design review should be planned as a continuous monitoring of a design to assure that it meets the expressed and implied performance requirements of the equipment during operational use. Such reviews provide periodic appraisal of the design effort to determine the progress being made in achieving the design objectives and can serve to systematically bring to bear specialized talent on specific problem areas. In addition, overall evaluations should be made to take into consideration specific design and interface problems that may be encountered later in the development and production cycle.

5. GENERAL DESIGN REVIEW GUIDELINES

Techniques for designing reliability into system/equipments usually are classified into three categories:

a. Conservative selection and application of piece parts.

b. Incorporation of redundant replacements and/or alternate modes of operation.

c. Minimization of environmental stresses; for example, electronic equipment must incorporate means for adequate heat rejection in order to provide reliable performance at thermal equilibrium. It cannot be overemphasized that high reliability can be achieved only if the electronic, thermal, and mechanical designs are well executed. The thermal design is fully as important as the circuit design. Ground-based electronic equipment is frequently installed in shelters having a ventilating or air conditioning system intended for the comfort of operating personnel. The cooling system for the electronic equipment must be made compatible with such a system.

Design reviews should begin with the conceptual phase that considers the broad general requirements and as the design approaches the hardware stage, narrows down to detailed meetings of reduced scope where only circuits, equipments, or portions of equipments are considered, and then broadens again as the various equipments are integrated into a system.

Design changes during the early design review phases generally require very little engineering effort since it usually involves only paper changes of a part, dimension, or value, although redesign of components might at times be mandatory. Design changes occurring during subsequent design reviews involving changes to drawings, modifications, or replacement of existing hardware, replacement of field supplies, revision of field manuals, or retraining of factory and field personnel for example, will be considerably more costly (100-1000 times) although the probability of such changes will be less than during the first phase. As it pertains to reliability, the periodic review of design at key points in the development program facilitates detection and correction of actual or potential design problems prior to finalization of the design.

The prime purpose of a formal reliability design review meeting must be to insure that adequate effort in reliability is being made. The design review process assures:

a. A means of solving interface problems;

b. Confidence that experienced personnel are involved in the design detail;

c. A record of why decisions were made;

d. A knowledge that systems will tie together and be compatible;

e. A total picture for the benefit and use of the final decision-maker in making trade-off decisions; and

f. A greater probability of a fully mature design.

A design review plan would include the time-phased events representing the appropriate milestones at which formal system/equipment reviews are made at major decisions points. The number of critical decision points will vary according to the type of development program underway. The broad categories are sometimes listed as:

a. Conceptual Design
b. Preliminary Design
c. Preproduction Design
d. Production Design

These review points are keyed to major events and consequently reflect the name of that event. It is well to bear in mind the objectives of these reviews and schedule the event accordingly. The main requirements that can be applied to any program will be covered by three or four major review points, namely:

a. Conceptual Design Review.
b. System Design Review.
c. Preliminary Design Review.
d. Detailed Design Review.

Regardless of the names assigned the design reviews, specific milestones or decision points must be identified where formal reviews will be conducted.

MIL-R-27542, paragraph 3.5.10, defines the requirement for contractor engineering design reviews for reliability. This paragraph requires the submission of a schedule of planned reviews to a procuring activity and permits the attendance of procuring activity personnel at these reviews. The technical ability of personnel required to participate in these reviews will vary according to the complexity of the system.

However, conceptual and system design reviews should be performed by experienced, senior engineers. Detailed equipment design reviews should be performed by engineers more closely associated with circuit design, parts application, etc. Again, the actual number of personnel participating in formal design reviews should be kept to a minimum commensurate with the specialists required for the problems to be considered. When such specialists as metallurgists or comparable authority are required, they should be scheduled to join the group at a specific time and then be dismissed as soon as possible.

It is also important to be alert to contractor methods of budgeting for scheduled design reviews to assure that costs are not compounded by each department participating in reviews. Design review costs will normally be proportional to the complexity of the equipment which dictates the number of reviews required as well as the number of personnel attending. A rule-of-thumb figure sometimes applied is that design reviews require 5% of the overall design-man-hours. The effort specifically oriented toward reliability is only a portion of this.

Design review milestones should be identified early in the program and should normally be coincident with the main development phases. The review points identified should be firmed up approximately 30 days in advance of a formal design review and data packages should be distributed to all attendees along with formal notification ten days prior to actual date a review is to be held. The specification MIL-R-27542 requires the

contractor to notify the AF procuring agency ten days in advance of a meeting so that they may participate if they so desire. In any case, the minutes, agenda, actions, and documentation should be available for review when requested by the procuring agency.

Specific information that must be reviewed and monitored during a contractor design review program includes:

a. Personnel (their experience levels) assigned to the program.

b. Organizational assignments, modus operandi, authority delegated to the Design Review Board.

c. Design handbooks and check lists prepared for design engineering use.

d. Design review plan--milestone identification, etc.

e. Data packages developed for design review use. These packages should include, as required, worst case studies, circuit analysis, parts application data, drawings, etc. The completeness of packages is very important for individual use in preparation for design reviews.

f. Recorded actions by a Board including rejected recommendations with reasons for rejection.

g. Approved design changes and their documentation.

h. Records indicating problem areas not resolved at the meeting, assignments for resolution, specific problems to be studied, target dates for completion, and methods of follow-up to assure completed actions.

i. Final approval of design by respective specialists by affixing signature on Board minutes.

The conceptual design review is the most important design review to be accomplished. Important decisions are made at this time that preclude or freeze subsequent designs. It is therefore logical that this review should be attended by the largest group of knowledgeable engineers. This Design Review Board must consider the feasibility of design; the techniques to be employed in achieving performance requirements; the interface problems which involve system maintenance, and design concepts; and specific design requirements that might conceivably push the state-of-the-art. Major design characteristics such as performance, reliability, maintainability, and value must be carefully considered. A proposed configuration should be reviewed for such considerations as the use of standard circuits of proven reliability, comparison of one computer manufacturer with another, evaluation

of belt-drive versus direct-drive, the need for redundant replacements, the hardware approach to be followed in the identification and localization of system failures, methods to minimize the influence of limited or critical life items on the operational capability of the system/equipment, etc. With such considerations a paper study may be accomplished to obtain an estimate of the system's reliability, maintainability, or other figures of merit. This study is then available as a valuable tool to assist the Board in selecting the ultimate system configuration. Although early reviews cannot be rigorous in design detail, the early design decisions are extremely important for these decisions commit the program to a specific design approach or strategy. Improper logic or design approaches should be ferreted out at this point where changes involve only paper changes and before actual equipments begin to take shape. As the design progresses, subsequent changes become much more expensive and tedious to accomplish.

The material or data that should be available for use by the Board in its preparation and deliberation includes:

a. The proposal;

b. The Specific Operational Requirement (SOR);

c. The Statement of Work and associated specifications;

d. The analysis of system requirements;

e. Basic design criteria (block or logic diagrams and flow charts);

f. Reliability and maintainability requirements;

g. Possible trade-off documentation; and

h. System/equipment schedules with milestones.

An important outcome of conceptual or system design reviews is the ability of the systems contractor to quantify reliability (and maintainability) requirements at the subsystem level for the guidance of design engineering personnel and for insertion into subcontracted equipment specifications.

Subsystems and component detail design reviews are concerned with determining the reliability characteristics of subsystems during the detail design phase of program development. The purposes of this effort are to determine the extent to which the various designs in process will achieve the requirements set forth as the result of the conceptual or system design review and to indicate the need for redistribution of system reliability requirements.

The number of formal, detailed subsystem design reviews scheduled and the optimum time for reviews will vary as a function of the system complexity, the type of equipment being utilized, the caliber of cognizant design engineers, etc. However, formal design reviews should be conducted prior to release of any design to production. At major review points every facet of the design considerations should be carefully gone over. A design review check list should be utilized to assure consideration of all important criteria. A check list may necessarily be tailored to fit the specific requirements of a system, but in any case it should not be a different set of criteria from the rules used by designers. It would be unreasonable to confront the designer with a new set of rules at the time of review. In some instances, depending on the size and scope of the program, it may be appropriate to provide or have the contractor develop a reliability design handbook to reflect the specific reliability requirements of the project to design engineers. Such design handbooks should be reviewed for adequacy of content and acceptability.

Development Engineering personnel of the Contract Management Regions should be fully utilized to provide continuous surveillance of the design review effort. This source of engineering talent is important to the SPO effort and should not be overlooked--their contribution can be of great value to the overall effort.

In any event, design reviews should not be staged affairs that reflect the results of previous meetings, but should indicate a thorough preparation and attention to detail by all participants. The design engineer should be prepared to defend all decisions reached by him by presenting required studies (including breadboard test data, if available), mathematical models, and engineering calculations. He should be prepared to defend the selection of a resistor, for example; not by merely stating that it is reliable, but by saying this resistor was chosen because it is a standard item with the lowest possible cost to perform the required function; it is derated to 25% of its normal rating for the following reasons...; it is considered as reliable as any item available based on the present state-of-the-art and is expected to give a long trouble-free life or MTBF of X hours.

Engineers attending reviews should be thorough in their pre-review analysis of what they consider as potential problem areas and should be prepared to indicate in detail the effects of their recommendation. It is also important that Board members notify the designer of areas of disagreement in sufficient time before the formal meeting to allow him to assemble reference material to support his decisions, thus allowing the Review Board to consider thoroughly both sides of the question. The complete analysis and presentation of facts rather than theories enables sound decisions to be reached in the shortest period of time. Examples of the types of data necessary to facilitate detailed reviews include:

a. System reliability predictions.

b. Detailed subsystem, circuit reliability predictions.

c. Component parts lists with appropriate test information.

d. Parts derating and application data.

e. Parts failure rate data (or sources).

f. Stress analysis results.

g. Failure effects analysis.

h. Statistical analysis of circuit (or assembly) performance as a function of parts variability. Error and tolerance studies.

i. Reliability aspect of redundant parts, assemblies, subsystems, modes of operation with attention to switching problems.

j. Consideration of potential reliability growth.

k. Documented reliability growth plans.

l. Analyses of known trouble areas, with plans for corrective action.

m. Technical data, including equipment physical construction and profiles, block diagrams, schematics, signal flow charts, equipment operating theory, maintenance philosophy, operating procedures and maintenance instructions.

While the above has been oriented toward formal Design Review Board actions, there should also be a general look at the interaction of a contractor's reliability and design organizations during program monitoring. The influence of the reliability organization on the design process must not be felt only at formal Board meetings. A continuous interaction on questions of design strategy should take place between these organizations throughout the design process.

It should be realized that reliability as well as other characteristics are affected by every decision made. This includes the choice and use of circuits and component parts, their arrangement, the environment in which the equipment will be used, and the operation of the equipment under field conditions. It should be emphasized that reliability is not the sole responsibility of a designer, nor should the design review be oriented in a direction such that designing becomes a responsibility of the design review team. Because of increased complexity of the equipment being designed, concurrency

concepts, and new devices and techniques being employed, it is impossible for a design engineer to maintain excellence in every technical discipline affecting the design process. The reliability design review, if properly performed, provides one of the most powerful and effective tools available to assure reliability program effectiveness through monitoring reliability as a design characteristic early in design or at the optimum stage of development.

The document Handbook for Reliability and Maintainability Monitors, AD611 577, from Defense Documentation Center, which has formed the basis for much of the material presented above, contains more detailed guidelines and checklists which can be used as a basis for scheduling and conducting reliability design reviews.

6. RELIABILITY TESTING

Reliability testing, or the evaluation of test data from a reliability point of view, provides the first tangible 'hard' results concerning the reliability of the design. The result of conducting a reliability analysis based on test data is thus very critical since it serves as the basis for many decisions such as those concerning design adequacy, assurances that required reliability under field conditions will be met, and the need for design changes. Therefore, the use of test data for reliability analysis should be very carefully planned and evaluated before it is accepted as a means of evaluation even though this approach probably provides the most effective and positive means for assuring reliability program effectiveness.

Details of reliability test and demonstration from an accept-reject and test time point of view are presented in Chapter 10, Reliability Measurement. However, reliability tests or test data which can be used to evaluate reliability many times can be applied long before reliability demonstrations, even those of a preliminary nature, are required. The availability of such data and its potential usefulness is an important note which should not be overlooked by the SPO or the contractor as a means for monitoring reliability progress. Use of such data can be used by the SPO as a criterion for evaluating contractor program effectiveness based on whether plans have been made for acquiring such data and/or such data are being used as it becomes available.

There are various sources of useful data depending on the type, size, and scope of the program and on the point in the life cycle at which a program may be. For instance, in a program involving the purchase of off-the-shelf hardware, data from performance tests and in-service use may be readily available. Even in initial stages of a development program there is usually data available on portions of the design under operational or performance/reliability oriented test conditions. Such data is usually available since very few development programs involve hardware in which

every element of the design is completely new. Even on those portions of the design on which such information is not available there is usually some development test or breadboard test data which has the potential for being used to evaluate reliability.

A key point related to using reliability testing, reliability demonstration testing, or test data to evaluate reliability is proper planning. This planning, in general, should be directed toward establishing (1) the means for recording or acquiring all relevant data including time, a description of test conditions, and conditions under which failures occurred and were recorded, and (2) a definition of system, equipment or component failure, and (3) the amount of data required to establish meaningful and valid conclusions. The following is a brief listing of the type information which is pertinent to a reliability analyses:

1. Identification either of equipment, system, or unit under test.

2. Test conditions and environments (bench test, room ambient, RFI, vibration, etc.).

3. Elapsed time indicator readings (standby and operate).

4. Date.

5. Test results.

6. Failure symptoms.

7. Elapsed time indicator readings at time of failure.

8. Corrective maintenance action to restore operation or a description of the cause of failure identified to the smallest replaceable item.

Data, particularly that which is acquired outside of regular or scheduled reliability tests or demonstration, should not be used indiscriminately since this can possibly result in drawing misleading conclusions.

In the plan to use reliability tests or other test data as a basis for evaluating/monitoring reliability, considerable thought should be given to using scheduled engineering tests that are required at various key points in a program life cycle. Tests such as Category I Tests, Category II Tests and Category III Tests often can be monitored to produce useful reliability oriented data. The use of these tests as a means for acquiring useful reliability data can have two advantages. One advantage is that data can be provided which reflects specific configurations and interfaces which are an integral part of the system so that reliability can

be evaluated along with and as early as other required engineering/performance characteristics. Those changes which may be required can be evaluated with respect to the total requirement, and they may be implemented more easily and less expensively when identified in early stages. The second advantage is that data oriented reliability evaluations can be achieved at a cost which is usually only a fraction of that required to conduct separate reliability tests. In addition to using these tests as an opportunity to gather data for evaluating reliability, in many cases they can probably be used to simultaneously fulfill the requirement for a formal reliability demonstration. Some approved reliability demonstration techniques are presented in ESDP 80-5, Verification of Quantitative Reliability Requirements (Decision Criteria) 15 November 1963.

7. TYPE OF TESTS

As mentioned above there are requirements for conducting various types of tests many of which are primarily engineering oriented. Broad guidance is provided in AFR 80-14, with some amplification in ESDP 375-2, A Typical Test Plan For Electronic Systems. However, implementation and the details of conducting tests and recording data are problems which must be resolved by the SPO. In addition, AFSCM 375-3, Chapter 6 and AFSCM 375-4, Chapter 3 of Part 4 provides information on various types of tests and their general objectives. Further information on establishing test time requirements and risks is presented in ESDP 80-5.

In general there are two categories of tests which can be used to provide information for supporting reliability evaluations. These are the measurements tests (i.e., tests designed to measure reliability), and evaluation tests (i.e., tests which generally result in a regression analysis designed to evaluate relationships between environments or stresses and parameters which influence the reliability of an item). Properly used, both categories of tests can be used to provide information for monitoring reliability progress or for identifying the potential areas where greater concentration is required to achieve reliability objectives. However it should be pointed out that the approach to planning, analysis, and use of results depends, in a large measure, on the category of test being conducted.

Since test data can be extremely valuable in monitoring, it is important to be able to identify the types of tests that are often applied. These tests (listed below) can frequently be used as sources of reliability oriented information provided, of course, that planning and preparing has been such that the appropriate reliability information will be recorded along with information normally obtained from these tests.

1. Qualification Test. This test simulates defined environmental conditions with a predetermined safety factor. The results of this test indicate whether a given design can perform its function within the simulated environment of a system: tests at this time are usually not made using production tooling and processes.

2. Preproduction Test. This is a test of design qualified hardware that is produced using production tooling and processes which will be used to produce the operational hardware. No production hardware should be accepted prior to satisfactory completion of this test. Test objectives include the gaining of confidence that production hardware is going to work; it will be reliable; it can be maintained and supported by the Air Force; and is not over designed.

3. Lot Acceptance Test. This test is based on a sampling procedure to assure that the product retains its quality. A specified number of items from each lot or group are withdrawn, at random, and tested to establish that the functions, tolerances, and materials have not degraded. No acceptance or installation should be permitted until this test for the lot has been successfully completed.

4. Individual Acceptance Test. This is based on a test of predetermined critical items to verify their operational characteristics prior to assembly into subsystems. Waivers to this requirement such as using the end item acceptance tests is not recommended as a production expediency. This test should be capable of being performed on the same fixtures used for preceding type tests.

5. Critical Weakness Reliability Test. This test determines the mode of failure when equipment is exposed to environments in excess of the anticipated environments. By this testing, critical levels can be determined for vibration, temperature, voltage, cycles, etc., which will adversely affect the component. In subsequent tests of the total system in which a stress level exceeds the expected limits, an evaluation of the critical weakness tests will provide excellent insight as to what may have been damaged or what can be expected to fail.

It should be pointed out that the assurance of reliability program effectiveness requires a continuous monitoring and evaluation based on various data developed either through design analysis or through test. As can be seen from above, a considerable amount of test data which is particularly useful as a means of evaluating reliability can often be made available in early stages through proper planning and utilization.

8. EVALUATING RELIABILITY PROGRAM PLANS AND ORGANIZATION

One of the first steps in assuring reliability program effectiveness is a thorough and in-depth analysis of the reliability program plan being offerred by a contractor and that which is subsequently implemented. In general the requirements for providing data describing the reliability program plan are presented in Data Item R-1 of AFSCM/AFLCM 310-1. As delineated in the Data Item R-1 a reliability program plan should include:

1. A detailed listing of specific reliability oriented tasks, analysis, and reviews including any plans for parts improvement effort or for new (or modified) military specifications which contain reliability levels being used by the contractor.

2. A description of the general procedures for implementing and controlling these tasks together with schedules where appropriate.

3. The means and schedule to be used for reporting accomplishment of these tasks.

4. A description of how required quantitative reliability objectives will be met during development and manufacture.

5. A description of the organization and personnel responsible for managing the overall reliability program.

6. A description of the responsibilities and functions of this organization and the authority delegated to it.

7. A description of the relationship between line, service, staff and policy organizations.

8. A description of the failure reporting system to be used including flow charts for analysis, feedback of corrective action.

9. A list of all equipments on which failure reports will be initiated and the point in time when failure reporting will commence for each.

10. A description of the plan for demonstrating at a specified time achieved reliability including estimated number of test articles and confidence. This plan should include trade-off curves showing number of test articles or cost versus confidence, and will include testing at the system, major element levels, such as a flight vehicle, and major subsystem or component levels separately and in combination, as applicable.

11. A description of the means to be used for ensuring that appropriate reliability requirements are included in subcontracts and the methods to be used for establishing such requirements.

Evaluation of a reliability program plan and organization can be considered to take place within two frames of reference.

1. Evaluation with respect to what is proposed and how it is described.

2. Evaluation with respect to what is implemented both with respect to what has been proposed as well as with respect to what should be implemented in order to achieve required reliability.

With respect to evaluation of proposed program plans, as well as evaluation of implemented effort, it should be remembered that the mere existence of a reliability program will not increase the reliability of an equipment, but an effectively monitored program will not permit an inadequate design to proceed into development, test, production, and use without specific management approval. It is this effective monitoring that will permit project engineers to assess feasibility of achievement and progress in time to make adjustments. Therefore, the process of evaluation and monitoring should be continuous in order to ensure effectiveness.

Guidance in conducting evaluation can be developed to considerable detail. However, it is more important for the SPO or project engineer to be aware of the functional and organizational and task relationships that are important and germane to a reliability program plan and implementation. For in this way, the SPO or project engineer can fit requirements to the particular project at hand. This offers the chance to provide much more in the way of flexibility and sensitivity to items which may be peculiarly important in significance or priority to a particular project either from a technical, schedule, or cost point of view. The following pages present information related to conducting evaluations of reliability program plans and organizations.

Evaluation of program plans and organizations should be heavily influenced by requirements as imposed by procurement documents. The general elements of a reliability program as required by Data Item R-1 mentioned earlier form the framework for development of a program plan. However, in making an evaluation, criteria other than those elements mentioned above should be used.

The following presents certain of these criteria which can be used depending on the nature of the program from a technical and cost point of view. Use of these items in a checklist format can provide an effective way of identifying program plan weaknesses and a means for comparing alternate plans in order to judge potential effectiveness.

Does the program plan provide for or include a description of:

(a) Close liason between personnel in the reliability program.

(b) A specific approach to reliability prediction.

(c) A critical effects analysis.

(d) A delineation of costs for reliability program tasks.

(e) A description of the procedures to be used in conducting design reviews.

(f) Indoctrination, training, and/or motivation of personnel in reliability.

(g) A data collection and correction action program.

(h) A schedule for submitting timely reports on results of analyses, predictions, and review.

(i) Reliability organizational relationships and responsibilities clearly defined and including relationships between reliability groups and other groups within the company organization.

(j) A definite means for reporting reliability status to top management and subsequent actions to be taken and a delineation of data sources to be used.

(k) Identifying and analyzing potential reliability problems in areas such as procurement, design, manufacturing, quality control, testing and logistic support.

(l) The procedure to be used in conducting critical analyses, the criteria to be used in identifying critical items and the specific action to be taken and the controls to be used to insure that appropriate action is taken.

(m) The tasks or work elements to be accomplished.

(n) The work to be accomplished under each task (task description).

(o) The time-phasing of each task.

(p) The man-loading assigned for the accomplishment of each task.

(q) Appropriate program plan milestone review points.

(r) Design review system, its method of operation, responsibilities, and authority.

(s) Corrective action system, including data collection system and proposed computational ground rules.

(t) Change order control system, with particular attention to the method by which the reliability organization has the opportunity to review all design changes for quantitative effects.

(u) The position of the reliability operation within the management structure, the organization of this operation, and the channels of communication between this organization and design engineering, quality control, test engineering, and components engineering.

(v) Alternative tasks as substitutes for those which may not be acceptable.

(w) Activities defined in terms of functions and accomplishments relating to the proposed equipment.

(x) Planned assignment of responsibilities for reliability program accomplishments.

(y) Internal "independent" reliability assessments scheduled to coincide with design progress.

(z) A reliability demonstration test program and which equipments, assemblies, or components will be tested, and to what extent.

From a subcontracting point of view, does the plan include a description of:

(a) The means that will be used to ensure that quantitative reliability requirements will be included in subcontracted equipment specifications.

(b) The means that will be used to ensure that each subcontractor has a reliability program which is compatible with the overall program.

(c) The procedure for reviewing subcontractor predictions and computations for accuracy and correctness of approach.

(d) The procedure that will be used to furnish subcontractors with failure data resulting from tests.

(e) The plan for requiring subcontractor progress reports and for reviewing subcontractor test plans for accuracy and correctness of approach.

(f) The means for ensuring that subcontractors have, and are pursuing, a vigorous corrective action effort on causes of unreliability.

In evaluating reliability program plans, it is also important to evaluate the organizational structure around which the plan will be implemented. One factor to be stressed is the importance of retaining the designer in the information and reliability activities information loop. The designer is the key to achieving reliability improvement and when made aware of problems and given adequate information, he can favorably influence design. In general, the reliability program plan should identify the position of the Reliability Group or Section within the overall organizational structure. Usually, the Reliability Group either is positioned as a line activity under engineering or combined with Quality Control (and perhaps other disciplines) to form a Product Assurance Department.

Most large companies will have a Reliability (or Reliability/Maintainability) Staff Officer (perhaps, Vice-President, Reliability and Quality Control) who is responsible for generating policy and standard operating procedures.

The main concern in studying an organization is to determine whether or not the proposed organization will be responsive to the overall program requirements, sensitive to problem areas, and able to contribute to the formulation of design criteria and the control of design for reliability.

Its ability to perform in accordance with the above is also a function of its personnel capability-mix. Since reliability encompasses a wide variety of tasks, ranging from complex modeling techniques to design criteria, a program plan should include information on the quality and quantity of people available to perform the proposed program.

In addition, the organizational structure should be such that:

(a) responsibilities for corrective action have been specifically assigned;

(b) responsibilities for establishing suspense dates for completion of the required action are clear;

(c) responsibility for follow-up to assure that actions are actually taken is delineated and that authority exists for ensuring response.

(d) responsibility for the assessment of the quantitative effect on reliability of actions taken is vested in a position of responsibility to accept or reject the approach;

(e) there is a point within the organizational structure where progress against various problem areas can be monitored.

Information kept at this point should include:

1. Definition or statement of a problem.

2. Corrective action contemplated.

3. Action agency or responsibility for problem resolution.

4. Effect of problem on reliability.

5. Action completion date.

9. EVALUATION OF IMPLEMENTED PLANS AND ORGANIZATIONS

Evaluation of implemented plans and organizations depends to a large extent on the plan and organization structure that has been proposed and/or approved by the SPO. During implementation, effort should be primarily directed toward making evaluations between what has been implemented versus what was proposed. Significant changes should be explained. The true test of the effectiveness of the program and organization, of course, is the impact on design and the resolution of problem areas. However, assuring reliability program effectiveness also requires personal first-hand monitoring. This monitoring should include discussions with technical and management personnel, examination of internal communication structure and the responsibility chain, an examination of the flow of information for problem recognition to resolution and acceptance, and a first-hand examination of the way in which informal as well as formal design reviews are conducted, as well as the way in which the requirement for test data is planned and satisfied.

The following briefly describes those evaluations which can be used to examine implemented plans and organizational structures. This same approach can be used with respect to various other items that are part of the overall plan.

. Engineers' predictions or estimates	versus	Published predictions
. Data feedback from tests	versus	Test log and test technicians' observations
. Engineers' description of design reviews	versus	Program plans
. Personnel from whom designers obtain reliability assistance	versus	Organizational structure
. Actual company-sponsored reliability training of technical personnel	versus	Documented company training program
. Actual availability of data on standard parts from past experience	versus	Stated or implied availability
. Designer's knowledge of reliability requirements, including environments and performance limits	versus	actual requirements
. Procurement personnel's considerations in vendor selection	versus	Program plan
. Part counts and stress analysis, from working drawings	versus	Those presented in prediction report

As mentioned earlier assuring reliability program effectiveness is a continuous process starting with the development of sound reliability requirements and continuing through participation in design reviews and test demonstrations. The entire process involves analysis, evaluations, and decisions based on qualitative information such as that contained in descriptions of proposed plans and that resulting from analysis of implemented effort and organizational structure as well as on quantitative information such as that resulting from predictions and tests. Since a program or organizational structure can only provide the framework within which meaningful activity or effort can be carried out, it is important that the SPO or project engineer make adequate provision for the technical support required to conduct the monitoring and analysis needed to assure reliability program effectiveness through the delivery of hardware which meets reliability requirements.

CHAPTER 7

FIELD DATA COLLECTION AND REPORTING

1. INTRODUCTION

The previous chapters of this notebook have discussed a variety of activities related to the management of a reliability program throughout the Conceptual, Definition, Acquisition and Operation phases of system development. These activities include tests for the measurement of the achieved level of reliability and, therefore, provide data applicable to system performance evaluation activities. However, these tests are generally concluded before the system is accepted by the using command, at which time the system is placed on an operational status.

The true measure of equipment and system reliability can only be determined after extended operation in the actual field environment. This "operational reliability" can, and often does, differ significantly from the levels predicted or demonstrated during system development. For example, reliability demonstration test data are evaluated based on certain assumptions concerning modes of failure and distributions of failure data. These factors, however, are based on experience gained on previous systems. A new system may not follow the assumed failure pattern, especially when this new system involves significant advances in the state of the art. Also, operational reliability is often strongly influenced by unpredictable stresses in the operational environment.

In view of unavoidable areas of uncertainty such as these, the need for extended monitoring and evaluation of equipment performance in its field environment becomes apparent. This need has prompted the establishment of formal programs for the continuing collection and reporting of reliability data generated during actual field operation. These field data collection and reporting programs are typically directed toward the analysis and evaluation of reliability data generated during the Operational Phase of the system life cycle, but are also applicable to analysis of data collected during certain Acquisition Phase activities, such as during Category II testing when field operational conditions are simulated.

Certain important characteristics of a field data collection and reporting system are discussed in this chapter. This discussion is intended to review the more important considerations in the management of a field data collection and reporting program. More detailed information concerning the design and implementation of such systems can be obtained in references listed in Chapter 12.

2. CHARACTERISTICS OF A FIELD DATA COLLECTION AND REPORTING SYSTEM

Ideally, the most effective field data collection and reporting system is tailored to the specific requirements of the system under consideration. However, because of the large number and wide variety of Air Force systems, a policy of providing a unique data collection and reporting procedure for each system would be impractical. Therefore, the Air Force has instituted a general purpose field data collection program to accommodate all operational systems. This program, which is implemented under AFM 66-1, "Maintenance Data Management," is intended to satisfy a variety of maintenance management and logistics data requirements, including the analysis of operational reliability factors.

The application of the AFM 66-1 Maintenance Data Collection System in the collection and reporting of field reliability data is discussed at the end of this chapter. However, due to the generality of the AFM 66-1 system, certain supplemental data may be necessary before specialized reliability analyses can be performed. In view of this, the discussion will be preceded by a brief discussion of the characteristics of a reliability data collection and reporting cycle, and some important factors to be considered in designing a reliability data collection and reporting system.

2.1 Reliability Field Data Collection and Reporting Cycle.

The basic functional elements of a typical reliability field data collection and reporting cycle are illustrated in Figure 7-1. Field failure reports are the primary vehicle for the collection of data concerning the operational reliability of systems and equipments. These reports not only provide a complete record of operational failures, but also contain data concerning operating time, environmental conditions, symptoms, and other data that are essential to the subsequent analyses.

Raw field data are prepared and processed as necessary to provide reliability information as required by various using groups. This processing is often performed by computer to permit timely analysis of the large volume of data obtained during the operation of complex systems. Further data analysis and investigation is often necessary to interpret the computer reports in terms of hardware design or system program management information appropriate for correction of weak areas in system performance.

Information developed by design or management groups are applied in modifying production or system management procedures.

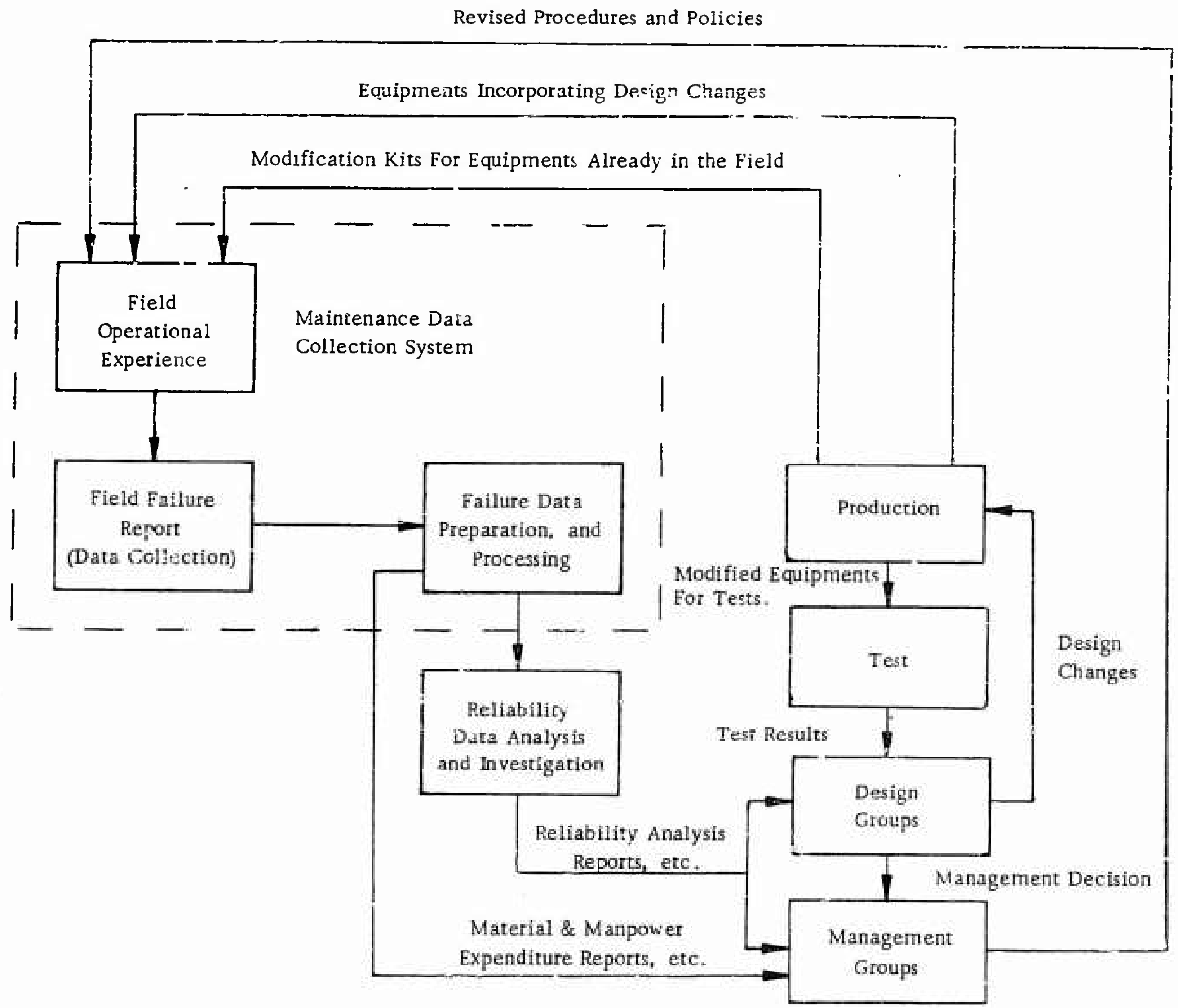


Figure 7-1. Basic Elements of a Reliability Field Data Collection and Reporting Cycle

Finally, the appropriate redesigned equipment, modification kits, or management policy revisions are returned to the field to alleviate the reliability problem.

The effectiveness of the reliability improvement action is evaluated by continuing the field data collection and reporting program. Thus, a reliability field data collection program becomes a continuing process of problem detection and evaluation, and design improvement monitoring.

2.2 Reliability Field Data Collection and Reporting System Design.

Reliability data from field operation are an essential aspect of reliability improvement. Data collection and reporting is not an objective in itself, however, but rather is an essential link in the chain of events leading to the ultimate objective of product improvement. Therefore, the design of an effective reliability field data collection and reporting system requires consideration of a variety of factors throughout the data collection and reporting cycle. These factors are discussed briefly below in the general order in which they should be considered. The first three of these, as summarized in Table VII-1, form the foundation for any data collection and reporting system.

a. Objectives of Data Collection and Reporting System. Before any data collection and reporting system can be designed, it is essential that the ultimate objectives of the system be clearly stated. The objectives of reliability data collection and reporting systems can be classified in three general information categories: (1) equipment failure patterns and cause and effect relationships, (2) parts usage information, and (3) operational effectiveness evaluations.

b. Analytical Techniques Required. The objectives of a data collection and reporting system effectively dictate the type of analytical techniques that will be required. For example, equipment failure cause and effect relationships are determined by means of analyses directed toward determining the frequency, significance and identification of equipment failure and thus will require statistical analyses of failure data to establish failure distributions and cause and effect correlations, and can involve analysis of the effect of part failure on overall equipment operation.

   Parts usage analyses also involve statistical analysis of part failure data, but are concerned with logistics aspects such as part provisioning requirements rather than equipment performance. Operational effectiveness analyses,

Table VII-1. Basic Considerations of Reliability Field Data Collection and Reporting System Design

Information Category	Type of Analysis on Data	Input Data Elements
A. Equipment failure patterns; classification of failures; environmental factors affecting failure trends.	Frequency, significance and identification of equipment failures. Part failure rate, failure distribution, and correlation analysis to ascertain cause-effect relationship.	1. Identification of failed part(s) a. Equipment (type, serial no. and manufacturer) b. Lowest designated assembly c. Circuit reference designation of failed part(s) d. Part manufacturer 2. Cause-of-failure information a. Symptoms b. Direct cause equipment wearout, operator error, etc.) c. Associated environmental factors such as weather conditions, power failure, etc.) 3. Operating time information a. Operating time,affected part(s) (date of installation, and date of failure, or actual operating time, if determinable) b. Equipment operating time - date and time of failure, running time, meter readings, duty cycle.
B. Parts usage; optimum stock levels	Prediction of spare parts provisioning requirements based on factors of part usage rate, re-provisioning rate, storage life, percent defective as received from vendor, shipment lead time and reorder point.	1. Part identification (stock or catalog number) 2. Associated equipment (type and manufacturer) 3. Defective stock information a. Deteriorated in storage b. Time in local storage c. Defective on receipt from source d. Source (manufacturer, vendor, depot) 4. Extent of delay in obtaining parts
C. Operational Effectiveness	Effect of equipment outage or degradation on operational mission. Reliability, availability, and similar analyses.	1. Equipment identification (type) 2. Date and time malfunction started, date and time cleared 3. Type of malfunction (catastrophic failure, calibration error, etc.) 4. Degradation of mission as result of malfunction

on the other hand, involve evaluating the effect of equipment outage on the operational mission of the overall system.

c. Data Input Requirements. The third important consideration in the design of a reliability field data reporting and collection system is that of determining specific types of data required in performing the analysis. In general, the data requirements are dictated by the type of analysis to be performed and the objectives of the analysis. For example, equipment failure pattern analyses involve part identification, cause-of-failure, and part operating time data. Part usage analysis are not normally concerned with cause-of-failure information, but require more detailed data concerning operating time, storage time, and reprovisioning time. Operational effectiveness analyses require data concerning equipment failure or degradation with respect to overall system performance and, therefore, do not usually require detailed part data.

The variety of data that might be provided by a typical reliability field data collection system is illustrated in Table VII-2. This list is not intended to be complete since specific analyses could require other types of data. Also, some of the data listed may not be essential in all cases.

d. Design of Data Collection Procedures. Once the data requirements have been established it will be possible to design a data collection procedure which will permit the appropriate reliability field data to be acquired, recorded and presented in a manner that will facilitate subsequent analysis. The major element of a data collection system is the field data report form on which raw field data are recorded. In fact, the field data report form is the communications link between the field operation and subsequent analysis activities. Thus, a well designed report form is one of the key elements of an effective field data collection and reporting system.

The design of a field data report form is a specialized activity involving the consideration of practical factors of system operation and support, as well as the more theoretical aspects of data analysis. In any case, however, a field data report form should meet the following general criteria:

Table VII-2. List of Items to be Included in Failure Report Form

(1) Report number

(2) Original report number

(3) Reporting contractor

(4) Work center or department

(5) System type, model, series

(6) System serial number

(7) Equipment type, model designation, model number

(8) Equipment serial number

(9) Failed item part number

(10) Failed item serial number

(11) Failed item name (noun)

(12) Failed item manufacturer

(13) Failed item reference designation (application)

(14) Next higher assembly part number

(15) Next higher assembly serial number

(16) Next higher assembly name (noun)

(17) Next higher assembly manufacturer

(18) Next higher assembly reference designation

(19) Replacement part number

(20) Replacement serial number

(21) Subsystem

(22) Date of failure (day, month, year)

(23) Operational usage at failure or removal (total time/cycles/miles by category, e.g., standby or operation, and environment)

(24) Total age of item

(25) Activity during which failed item discovered, e.g., calibration, checkout, countdown, launch, preflight, flight, etc.

(26) Initial, subsequent, and final disposition (condemned, repaired, found serviceable, etc.)

(27) Effect of failure (mission failure, performance degradation, no significant effect)

(28) Type of failure (primary or secondary)

(29) Cognizant action agency

(30) Analysis required (yes or no)

(31) Narrative description of trouble (how malfunctioned)

(32) Failure analysis report number

(33) Disposition approval signatures

- The form should permit recording of all essential data in a format compatible with the analysis to be performed. However, superfluous data should not be recorded.

- The form should be conducive to accurate data recording. Confusing format, inadequate instructions and other sources of human error should be minimized.

- The data should be presented in a format suitable for direct use in subsequent data processing. This includes appropriate coding for computer processing when warranted.

e. Data Processing. Reliability data processing may be accomplished either manually or by electronic data processing methods. The data processing procedures used are usually dictated by economical factors and by the volume of data to be handled. In general, electronic data processing is applicable in processing reliability data obtained from large-scale or widely-used systems,while manual processing is more appropriate for processing data from small scale or one-of-a-kind systems. For example, failure data from operational tests, such as a Category III test, can usually be processed by manual means. However, the same system deployed in large numbers for field use will probably generate sufficient volume of data to justify the application of electronic data processing procedures.

The particular data processing procedure to be used should be established at the time the analytical techniques and data input requirements are established. This will permit the design of a data collection system that is compatible with the data processing system as well as with the input data requirements.

3. AIR FORCE MAINTENANCE DATA COLLECTION SYSTEM

The Air Force has instituted a maintenance-oriented field data collection system that is intended to provide data necessary for management of the system maintenance resources. This system, which is described in Air Force Manual AFM 66-1, is used primarily for base-level management within the Chief of Maintenance complex. Thus, the data collected are primarily related to maintenance control and maintenance manpower management. However, the system is also designed to provide data to the Air Force Logistics Command (AFLC)

for material management and logistic support requirements. Therefore, the AFM 66-1 Maintenance Data Collection System provides for the collection of certain types of data that are useful in reliability analyses.

Some of the analyses that are possible using data obtained by the AFM 66-1 system are:

a. Analysis of high system failure rate and high part consumption.

b. Analysis of component and end item data to screen out parts which are exhibiting a wide variation in failures between different installations of the same system.

c. Identification of unreliable items and substantiation of product-improvement action.

The primary problem in utilizing the AFM 66-1 Maintenance Data Collection System for the collection of data for reliability analyses is that the Maintenance Data Collection Forms (AFTO Forms 210, 211, and 212) do not directly provide quantitative measurement of time to failure, elapsed time, and other data that would provide a direct analysis of an achieved level of system reliability. However, this problem can usually be alleviated by the use of supplementary forms for the collection of the additional data. With the use of computers, data from various sources such as this can be combined to produce meaningful reliability information for use by management and design groups.

CHAPTER 8

RELIABILITY ALLOCATION

1. INTRODUCTION

Reliability allocation is the process of establishing reliability requirements or goals for various subdivisions of a system. The objective of performing a reliability allocation analysis is to arrive at reasonable goals for each subdivision to assure the achievement of the required level of overall system reliability.

Reliability allocation, or apportionment, is closely related to reliability prediction. A prediction of system reliability is usually obtained by determining the reliability of the lowest level items and proceeding through intermediate levels until an estimate of system reliability is obtained. Reliability allocation begins with a statement of the overall system reliability requirement and apportions this total requirement among subsystems and lower subdivisions constituting the system.

In actual application there is considerable overlap between prediction and allocation. An allocation, usually performed early in a development program, helps to establish a design approach for meeting a system reliability objective. As the design progresses, predictions are performed to evaluate the degree to which the system reliability objectives are being met. For example, during the definition and early acquisition phase of the system life cycle, allocations are often performed to aid in the development of alternate design approaches, while predictions are performed to assess the impact of proposed design changes on system reliability.

Some of the advantages of reliability allocation are:

a. Reliability requirements are apportioned among the various parts and units of the system before system design becomes committed to a particular design approach.

b. Attention can be focused on the reliability relationship between various subdivisions of the system and on the contribution of each to overall system reliability, early in the design stage when design changes can be made more easily and economically.

c. A judicious apportionment based on pertinent factors will result in placing realistic reliability requirements among subsystems and lower subdivisions throughout the system.

d. The possible need for specific reliability design effort, such as the application of redundancy, can be established during the conceptual phase and, therefore, can be considered in preparation of the developments specifications.

Although allocations are performed by the program manager to set down the main reliability goals and guidelines, apportionment analysis can also be an activity of prospective contractors in preparing contract definition proposals. Familiarity with techniques and meaning of reliability allocation can place program managers in a position to evaluate contractor proposed subsystem and equipment reliability objectives, the methods by which they were established and proposed design approaches to meeting reliability requirements.

Some basic allocation techniques are discussed in this chapter, beginning with the quantification of mission requirements in terms of system and subsystem reliability, and continuing through the allocation to lower subdivisions. It should be noted, however, that these techniques will be effective only to the extent that the allocated values are actually achievable.

2. MISSION REQUIREMENTS AND SYSTEM RELIABILITY

As previously indicated, reliability allocation is an important input to establishing system and subsystem design approaches for meeting reliability objectives. These objectives, however, are not always defined in terms conducive to direct identification of quantitative reliability requirements. In fact, during early conceptual and definition phases, when allocations are most beneficial, system reliability requirements may only be implied in the operational mission description or, at best, are included together with factors such as maintainability in defining an overall availability requirement. Therefore, mission-oriented requirements must be expressed quantitatively, and in terms of parameters associated with reliability measurement before an effective allocation can be performed.

Interpreting system performance requirements in terms of reliability is one of the functions of the reliability program during early phases of a system life cycle when reliability requirements are only implied in operational mission descriptions. This interpretation must be performed in a manner that will permit quantitative allocation of system reliability requirements among various subsystems. This requires proper interpretation of statements defining mission-oriented performance requirements, and quantification of these requirements in relation to operational time parameters in such a way that compatible and practical reliability requirements for the system can be established. Alternatively, an initial trade-off study may be required to optimize the balance between reliability and maintainability in achieving a specified level of availability.

2.1 Typical Performance Requirement Statements

Performance requirements for different systems vary considerably depending on the purpose of the system, and the expected mission. Performance requirements, as usually specified in early system requirements documentation, are concerned more with what is to be done than with how it is to be accomplished. For example, a ground radar system might be required to achieve a probability of mission success of 80% of detecting a 10 square meter aircraft target flying at an altitude of 50,000 feet, and at a range of 200 miles. These requirements are quite different from those for a surface to air missile system which might require a 90% kill probability (i.e., mission success) on a target having a speed of mach 2, and at an altitude of 100,000 feet.

Operational mission requirements stated in terms such as these do not directly provide system reliability requirements. However, a quantified system reliability statement can usually be developed by considering such performance requirements together with additional information defining other aspects of the planned mission.

2.2 Reliability-Oriented Quantification of Mission Requirements

Performance-oriented statements of mission requirements, such as those mentioned as examples in paragraph 2.1, usually include information from which some form of system reliability requirement can be derived. However, such statements will often require a certain degree of interpretation and even some assumptions. For example, even though reliability is a function of mission time constraints, the intended mission may not be defined quantitatively in relation to time. In fact, many systems are not intended to perform uniquely definable missions, but rather are intended to meet a variety of possible mission requirements. In these cases, mission time factors cannot be precisely defined and certain assumptions are necessary.

For a simplified example of a procedure for interpreting performance requirements in terms of reliability, consider the performance of a radar set which has a mission success requirement of 80%. This requirement could be met by a failure-free system having exactly a 80% probability of detecting the specified target at 200 miles. However, any real system will have some probability of failure. Therefore, the design of such a system must be such that the probability of detection is greater than 80% when the system is operational to compensate for the chance of a failure during an operational requirement.

In its most elementary form, the problem would reduce to obtaining a probability of at least 0.80 that the system: (1) is not in a failed condition at the time the target approaches, (2) remains "up" for the time required for detection, and (3) detects the target. If the system is designed such that the actual probability of detection is 96%, then the probability of being, and remaining "up" must exceed 0.80/0.96 or 83.3%. This probability of being "up" and remaining in the "up" state is a function of the availability and reliability. In this particular case, the availability, A, can be defined as the probability of being "up" at any given time. This quantity is a function of restore or repair rate (maintainability) as well as failure rate and, therefore, is beyond the scope of this chapter. For the purposes of this example, a value of A = 0.90 will be assigned.

The required reliability can now be established using the relationship $A \cdot R = .833$. Substituting the value for A gives:

$$R = \frac{0.833}{0.90} = 0.926$$

Therefore, to meet its performance requirements, the radar system should have a reliability of at least .926 for the time required for target detection. Further definition of the required system reliability would require more complete definition of mission and operational time constraints.

2.3 System Reliability Requirements

System reliability requirements are usually stated with reference to a required probability of satisfactory operation over a stated interval of time. Therefore, allocations at the system level are usually performed on a probabilistic basis. In the event system MTBF or mean life requirements are specified, conversion to a reliability or probability of survival requirement can be performed before proceeding with an allocation analysis. Such conversions are performed using techniques involving statistical failure distribution functions as described in Chapter 10.

At times, the information available at the time an allocation is to be performed does not permit a direct calculation of reliability requirements. Such a case might exist when mission-oriented system reliability or MTBF requirements cannot be established because of a lack of mission profile data. In such cases, a gross allocation can be performed based on techniques such as the reliability prediction by function or other procedures for obtaining gross reliability estimates. These procedures permit an estimate of the achievable system reliability based on elementary performance-oriented information. Several procedures for performing analyses

to obtain gross reliability estimates that are applicable in performing allocations are discussed in Chapter 9. (see Table IX-2).

3. RELIABILITY ALLOCATION TO SUBSYSTEMS

Once a system reliability requirement has been established, it will usually be necessary to apportion the overall reliability among several subsystems. Several basic techniques are available for allocating system reliability to the subsystems. The particular technique to be applied in a given situation would depend on many factors such as the amount and type of data available and the overall configuration of the system. Some of the techniques available are described below in the order of increasing complexity. It should be noted, however, that the allocation schemes presented here will be valid only to the extent that the final allocated figures are achievable by the components to which they are assigned. If reliability allocations are not achievable, redundancy may be required to meet the overall system objective. Reliability allocations in redundant systems involves complex modeling procedures and iterative analysis techniques that are performed to trade-off reliability with cost and weight penalties. Such techniques are beyond the scope of this chapter and will not be discussed here. However, some of the procedures mentioned in Chapter 9 for degradation analysis prediction techniques are similar to the procedures that would be used in these complex allocations.

3.1 Equally Critical Subsystems in Series Configuration

The most elementary procedure for allocating an overall system reliability among several subsystems assumes that all subsystems are effectively connected in series and are equally critical to system operation, (i.e., the failure of any one subsystem would result in system failure). Also, it is assumed that all subsystems are equally complex. In such a case, the system reliability is apportioned equally among all subsystems.

In a system with equally critical and complex subsystems connected in series, the overall system reliability (probability of survival) is equal to the product of the reliabilities of the subsystems. This can be expressed

$$R_s = R_1 \cdot R_2 \ldots R_n$$

where:

R_s = the reliability of the system

$R_1, R_2, \ldots, R_n$ = the reliabilities of subsystems number 1, 2, . . . , n respectively.

If all subsystems are equally critical and complex, then $R_1 = R_2 = \ldots R_n$. In this case the system reliability is $R_s = R^n$, where R is the reliability of any one of the n subsystems. Thus, each subsystem would be assigned a reliability of:

$$R = R_s^{1/n}$$

Example:

Assume a system consists of three subsystems of equivalent complexity in a series configuration. If the required system reliability is $R_s = 0.95$, the reliability allocation to each subsystem (i. e., the reliability goal established for each subsystem) would be:

$$R = (0.95)^{1/3} = 0.983$$

3.2 Non-Equivalent Subsystems in Series Configuration

Very often, as more information concerning the subsystems becomes available it may become apparent that the subsystems are not "equivalent" and that each subsystem should be assigned a different weight in its contribution to system reliability. One method of reliability allocation which uses a weighting to account for subsystem complexity is described below. A similar technique can be devised for weighting by other factors such as criticality or operational priority.

Relative subsystem weights based on complexity can be calculated using:

$$W_i = \frac{C_i}{C_1 + C_2 + \ldots C_N}$$

where:

W_i is the weight assigned to the i^{th} subsystem,

C_i is the complexity of the i^{th} subsystem as measured in terms of a particular type of complexity, such as parts count, or active element group (AEG) count.

The reliability allocation to the i^{th} subsystem can be calculated using:

$$R_i = \left[R_s \right]^{W_i}$$

where:

R_i = allocated reliability for the i^{th} subsystem

R_s = required overall system reliability

W_i = the weight assigned to the i^{th} subsystem

Example:

Assume a system consists of three subsystems in series, and the overall system reliability requirement is 0.95. Also assume that the complexity (AEG count) of the subsystems are:

Subsystem 1: $C_1 = 200$

Subsystem 2: $C_2 = 300$

Subsystem 3: $C_3 = 500$

The weights assigned to each subsystem for the purpose of reliability apportionment are:

$$W_1 = \frac{200}{200 + 300 + 500} = 0.200$$

$$W_2 = \frac{300}{200 + 300 + 500} = 0.300$$

$$W_3 = \frac{500}{200 + 300 + 500} = 0.500$$

The reliabilities can now be allocated to Subsystems 1, 2 and 3, respectively, as follows:

$$R_1 = \left[0.95\right]^{0.200} = 0.990$$

$$R_2 = \left[0.95\right]^{0.300} = 0.985$$

$$R_3 = \left[0.95\right]^{0.500} = 0.975$$

These values can be checked by calculating the system reliability as the product of the subsystem reliability such that

$$(0.990)(0.985)(0.975) = 0.95$$

3.3 Consideration of Subsystem Importance and Complexity

A study by the Advisory Group on the Reliability of Electronic Equipment (AGREE) recommended apportioning system reliability based on the importance of the subsystem to system operation, as well as the relative complexity of the subsystems. The mean time between failures is apportioned to a particul r subsystem using the expression:

$$m_i = \frac{k_i t_i}{\left(\frac{n_i}{N}\right)\left(-\ln R_s\right)}$$

where:

m_i is the MTBF of the i^{th} subsystem

k_i is the probability that the system will fail if the i^{th} subsystem fails

t_i is the operating time of the i^{th} subsystem during the specified mission

n_i is the total number of modules in the i^{th} subsystem

N is the total number of modules in the system

R_s is the required system reliability

This technique is applicable to series systems in which failure of a subsystem will cause system failure with probability, k. The quantity n_i/N is the relative complexity of the i^{th} subsystem, and can be calculated in the same manner as w_i in paragraph 3.2. The subsystem operating time, t_i represents the time the i^{th} subsystem would be required to operate in completing the defined mission.

Example:

Consider a system with a reliability requirement of 0.9 for a ten hour mission. The system consists of three subsystems A, B and C. Subsystem A consists of 10 modules and operates for the entire mission; if a module within A fails the system fails with certainty. Subsystem B consists of 20 modules and operates for five hours during the mission; if a module within B fails the probability of system failure is 0.9. Subsystem C consists of 8 modules and operates for the entire mission; if a module within C fails the probability of system failure is 0.5.

Table VIII-1 gives the value of k, n, and t for Subsystems A, B and C and the required MTBF's, based on the reliability requirement of 0.9.

Table VIII-1. Reliability Apportionment Based on the AGREE Technique

Subsystem	k	n	t	m
A	1	10	10	362 hours
B	0.9	20	5	81 hours
C	0.5	8	10	226 hours
		N=38		

As a check on the apportionment technique, the resulting system reliability may be calculated. The system reliability is given by:

$$R_s = R(A)\,R(B)\,R(C)$$

The reliability of an individual subsystem is determined from:

$$R(i) = 1 - k_i\left(1 - e^{-t_i/m_i}\right)$$

Substituting for specific subsystems:

$$R(A) = 1 - 1\left(1 - e^{-\frac{10}{362}}\right) = 0.972$$

$$R(B) = 1 - 0.9\left(1 - e^{-\frac{5}{81}}\right) = 0.945$$

$$R(C) = 1 - 0.5\left(1 - e^{-\frac{10}{226}}\right) = 0.978$$

The system reliability is then equal to the product of these values, or 0.90. From this it would be concluded that the system reliability requirement could probably be met by apportioning reliability requirements to the subsystems as indicated above.

4. RELIABILITY ALLOCATION TO EQUIPMENT AND LOWER SUBDIVISIONS

The techniques mentioned in paragraph 3 for allocating system reliability requirements involves considering a probability of system survival requirement and establishing compatible subsystem reliability requirements. At the time during the system life cycle when such allocations are performed, the data necessary for more definitive allocation are not available. However, subsequent allocations to equipments and lower levels will normally be performed later during the development cycle when more is known about the system and subsystem design. For example, at a certain stage of the design, preliminary reliability predictions will have been performed, and gross failure rate predictions will be available. At this stage, it is often desirable to allocate maximum subsystem failure rate limitations to lower levels of hardware design and thereby provide detailed design goals to be stated in terms that are free of mission time parameters. One example of a technique for allocation of failure rates rather than reliability, which permits direct application of available failure rate data, is described below.

4.1 Allocation of Failure Rates in a Series Configuration

One useful technique in allocation of failure rates to lower subdivisions considers the relative complexity of the various subdivisions. This technique is based on the assumption that the failure rate of a series system with N subdivisions is the sum of the subdivision failure rates. If the maximum allowable

system failure rate is given by λ_{max}, this value must be apportioned so that the subdivision failure rates λ_i satisfy the following:

$$\lambda_1 + \lambda_2 + \ldots \lambda_N \leq \lambda_{max}$$

Let the estimated complexity of the subdivisions be given by $C_1, C_2, \ldots, C_N$.[1] The relative element weights are calculated using:

$$w_j = \frac{C_j}{C_1 + C_2 + \ldots C_N}$$

The apportioned failure rates are then determined for each individual element by:

$$\lambda_j = w_j \lambda_{max}, \quad (j = 1, 2, \ldots, N)$$

Since $\sum_{j=1}^{N} w_j = 1$, the failure rates are apportioned so that

$$\sum_{j=1}^{N} \lambda_j \leq \lambda_{max}$$

Example:

Consider a subsystem consisting of three equipments: a power supply, a receiver, and a transmitter. The maximum allowable subsystem failure rate is 0.005 failures per hour (an MTBF of 200 hours).

A failure in either one of the three equipments will cause a subsystem failure. The complexity of each equipment has been determined as follows:

Power Supply:	100 parts
Receiver:	225 parts
Transmitter:	560 parts

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[1] The "complexity" of an item is a measure of the number of elementary parts making up the item. In general, complexity is determined by parts count based on available design data. If necessary, the complexity can be estimated based on known complexity of similarly constructed items performing comparable functions.

The weight assigned to each module is then:

$$W_{(\text{Power Supply})} = \frac{100}{100 + 255 + 560} = .11$$

$$W_{(\text{Receiver})} = \frac{255}{100 + 255 + 560} = .28$$

$$W_{(\text{Transmitter})} = \frac{560}{100 + 255 + 560} = .61$$

The failure rates can then be apportioned as follows:

Power Supply:	0.11(0.005)	= 0.00055
Receiver:	0.28(0.005)	= 0.00140
Transmitter:	0.61(0.005)	= 0.00305
System:		= 0.00500

5. IMPLEMENTATION

The preceding discussions describe some of the techniques commonly used in allocating system reliability requirements to lower subdivisions. The primary purpose of such allocation is to provide a guide for the development of reliability design goals, and for providing subsystem reliability requirements for procurement specifications. For example, a gross system reliability requirement can be allocated to the various subsystems in a manner that considers practical aspects such as complexity, system configuration and operational priority. Further allocation of subsystem reliability can provide compatible failure rate goals applicable to the design of lower subdivisions.

In addition to providing design goals, appropriately developed reliability allocations can provide valuable input for activities such as reliability feasibility analyses, preliminary reliability modeling, cost effectiveness studies, and any of many design trade-off analyses performed during system development.

The techniques mentioned here are only a few of the procedures that come under consideration when performing reliability allocations for complex systems. In an actual case, the allocation procedures will be selected based on many factors such as system function and mission requirements, and may involve complexities such as the consideration of a variety of missions, and missions that vary with time (i.e., the probability of needing a given system function may change as a mission

progresses). Therefore, in a practical case all such factors must be defined before an effective allocation can be performed. Appropriate techniques are usually selected as a part of the overall reliability engineering task.

In selecting and applying the allocation techniques, however, it should be noted that the resulting allocations will be valid only if the final allocated values are achievable by the components to which they are assigned. If these allocated levels of reliability are not achievable, redundancy will be required. In this case, a much more complex scheme must be designed to trade off reliability with cost and weight penalties to establish an optimized system configuration.

Overall system reliability requirements are usually allocated to subsystems during the Conceptual Phase to provide reliability requirement for the preliminary technical development plan (PTDP), and for the contract definition phase RFP. Allocation techniques also are invaluable to contractors in performing trade-off studies, developing reliability design requirements for contract end items (CEI), and performing other tasks associated with proposal development during contract definition. In addition, original and up-dated allocations provide the basis for the development of criteria for performing the technical evaluation of competing contractors' proposed system reliability engineering approaches.

CHAPTER 9

RELIABILITY PREDICTION

1. INTRODUCTION

Reliability prediction is the technology of estimating the level of reliability that will be achieved by a system on the basis of functions and characteristics of the system design and the expected operating environment. Reliability predictions provide a means of quantitatively assessing system reliability before hardware models are constructed and tested. Thus, they are an important aspect of system development and engineering, and have important applications throughout the conceptual, definition and early acquisition phases of the system life cycle.

The several reliability prediction methodologies in common use permit reliability analyses to be performed with varying degrees of detail and provide useful evaluations of system reliability, even while the system is in the early stage of development. For this reason, reliability predictions are valuable tools in performing a variety of essential tasks as the system development program progresses.

1.1 Reliability Prediction Applications

System development tasks involving significant prediction activity can be classified in seven general task categories: feasibility study, allocation study, design comparison, proposal evaluation, trade study, design review, and design analysis. These task categories differ in principle objective, and are performed at different stages of the development program. However, the associated reliability predictions are performed using essentially the same basic procedure for any task category; the major difference in procedure being dictated by the particular phase of the system life cycle rather than by the objective of the task. The purpose and characteristics of the various task categories, and the relationships of reliability predictions to the task objective are summarized in the following paragraphs. These tasks typically are the responsibility of either the Air Force or Contractor, and are performed during different phases of the life cycle, as illustrated in Table IX-1.

a. Feasibility Studies. Feasibility studies are performed as a part of the exploratory development, advanced development, system study, and system engineering activities of the Conceptual Phase. In general, feasibility studies are directed

TABLE IX-1 RELIABILITY PREDICTION APPLICATIONS

	CONCEPTUAL PHASE		DEFINITION PHASE			ACQUISITION PHASE
	Development	Transition	Preparation For C. D.	Contract Definition	Review & Decision	
Feasibility Study	AF	AF				
Allocation Study		AF	AF	C		C
Design Comparison			AF	C	AF	
Proposal Evaluation			AF		AF	
Trade-Off Study				C		C
Design Review						AF
Design Analysis						C

AF	Tasks typically performed by SPO or other Air Force activities.
C	Tasks typically performed by Contractor.

toward evaluating the feasibility of given technological approaches in meeting operational objectives within the practical constraints of time and cost. However, in most systems severe operational requirements generate additional constraints in the area of system effectiveness. Therefore, an evaluation of the probable level of system reliability that will be achieved by the approach in question is a critical factor in the feasibility analysis. Such evaluations of system reliability involves reliability predictions based on extremely gross system performance and environmental data.

b. Allocation Study. During the late Conceptual Phase, and during Contract Definition, a series of progressive studies are performed for the purpose of allocating overall system effectiveness requirements among the several subsystems and elements of the system. System effectiveness, which is a measure of the system's ability to perform as required, includes system reliability as a major parameter. Therefore, a significant portion of the allocation studies involve the allocation of system reliability. During such studies, reliability prediction procedures are applied as the primary analytical tools of reliability allocation. (The general subject of reliability allocation is reviewed in Chapter 8.)

c. Design Comparison. During the Definition Phase, alternate designs of established feasibility are compared in selecting the particular approach(s) to be considered for further development. Such comparisons typically are performed by the contractors during the contract definition studies, and by the Air Force SPO in evaluating the results of the various competing contractors efforts. Reliability is a major parameter in the effectiveness of a given design and must be considered in any comparison of alternate designs. Thus, the probable level of system reliability, as determined by means of reliability predictions, become an important aspect in comparing alternate designs.

d. Proposal Evaluation. Evaluation of competing proposals for contract definition studies, and subsequent evaluation of Acquisition Phase proposals resulting from the contract definition effort involve careful analysis of many factors such as cost, contractor capability and proposed design approach. In general, proposals are evaluated in terms of many interrelated factors. One of these factors is an evaluation, usually by means of a reliability prediction, to verify the reliability

of the proposed design. Such evaluation requires a reliability prediction which is directed toward assuring that at least a minimum acceptable level of reliability will be realized. This is not normally as vigorous as a prediction performed for the purpose of estimating the actual value of reliability, as might be required in design comparison studies.

e. Trade-Off Studies. Trade-off studies are usually an integral part of the development and design activities during the Definition and Acquisition Phases. Trade-off studies can involve any of many sets of interrelated design factors. However, in most cases, physical and functional design characteristics are traded against each other within constraints of system operational effectiveness, operational requirements, and physical restrictions. Thus, reliability predictions as the trade-off areas are varied are important aspects of any trade-off study because of the relationships between system effectiveness and reliability.

f. Design Review. During the Acquistion Phase, official design reviews are performed at appropriate stages of system development to assure that the design is progressing according to the baseline requirements. These design reviews include an assessment of every aspect of design, including the achieved level of reliability. Therefore, a reliability prediction performed at a level of detail that considers elementary details of hardware design usually forms an important part of analysis performed in support of a design review.

g. Design Analysis. As a system design progresses throughout the development stage of the acquisition phase periodically updated reliability predictions are invaluable to the contractor in identifying reliability problems that may be generated, assessing the effect of design change, and otherwise measuring the progress of the design with respect to the achieved reliability. In addition, specialized design analyses involving reliability predictions are performed for such purposes as supporting maintenance, logistics and test program planning studies.

1.2 Reliability Prediction Techniques

Several reliability prediction techniques, varying in level of complexity and detail of application, are available to the reliability engineer. In general, the techniques in current use provide means for predicting total equipment or system reliability as a function of its defined design or functional characteristics. Also, to the extent possible considering the maturity of available data,

most prediction techniques consider the statistical distribution of failures to permit reliability evaluation in a quantitative manner.

As mentioned in paragraph 1.1, reliability predictions have a variety of applications, and must be performed at various times throughout the system life cycle beginning during the Conceptual Phase, and continuing through the Definition and Acquisition Phases. During this time span, data describing the system design evolves from a qualitative description of systems functions to detailed specifications and drawings suitable for hardware production. Therefore, reliability prediction techniques have been developed to accommodate the different reliability study and analysis requirements as the system design progresses. These techniques can be roughly classified in six categories, depending on the type of data or information considered in the analysis. These categories are:

a. Similar Equipment Techniques. The equipment under consideration is compared with similar equipments of known reliability in estimating the probable level of achievable reliability.

b. Similar Complexity Techniques. The reliability of a new design is estimated as a function of the relative complexity of the subject item with respect to a "typical" item of similar type.

c. Prediction by Function Techniques. Previously demonstrated correlations between operational function and reliability are considered in obtaining reliability predictions for a new design.

d. Part Count Techniques. Equipment reliability is estimated as a function of the number of parts, in each of several part classes, to be included in the equipment.

e. Stress Analysis Techniques. The equipment failure rate is determined as an additional function of all individual part failure rates, and considering part type, operational stress level, and derating characteristics of each part.

f. Degradation Analysis Techniques. Circuit tolerances, parameter drift characteristics, part variation, and other factors are considered together with stress levels in predicting the probability of circuit malfunction due to wear out or other types of degradation.

Reliability prediction techniques in each of these categories are described in subsequent paragraphs of this chapter following a brief discussion of some of the underlying mathematical principles of reliability prediction.

2. MATHEMATICAL FOUNDATION OF RELIABILITY PREDICTION

The reliability prediction techniques in common use are founded on the accepted basic definition of reliability, i.e., the probability that a system, subsystem or equipment will perform a required function under specified conditions without failure for a specified period of time (see AFR 80-5). This probabilistic definition has permitted the application of basic probability theory in stating the fundamental concept of reliability and, from this, developing the mathematical foundation of reliability prediction.

2.1 Probabilistic Concept of Reliability.

Consider an item (system, subsystem, etc.) for which there are n possible causes of failure, and where C_i represents the i^{th} cause of failure ($i = 1, 2, \ldots, n$). If the probability of occurrence of cause C_i is $P(C_i)$, then the conditional probability of the occurrence of a failure (F) due to cause C_i is $P(F/C_i)$. Applying the rules for combining statistically dependent events (one event must have occurred before the other can occur) the probability of the cause and failure occurring is $P(C_i)P(F/C_i)$.

This represents the probability of a failure occurring. However, reliability is a measure of the probability of performance without failure. Therefore, the basic mathematical definition of reliability considers that a given cause and resulting failure will either occur or not occur so that the probability of the item failing due to cause C_i plus the probability of not failing due to cause C_i is equal to 1. By definition, the reliability of the item with reference to cause C_i is the probability of not failing due to cause C_i, or:

$$R_i - 1 - P(C_i)P(F/C_i) \tag{1}$$

Defining the reliability of the overall item as the probability that there will be no failure due to any of the n possible causes, provides the fundamental concept of reliability which is stated:

$$R = \prod_{i=1}^{n} \left[1 - P(C_i)P(F/C_i) \right] . \tag{2}$$

This expression can be simplified in practical cases by assuming that if a cause of failure occurs, then a failure must occur, otherwise the cause must not have occurred. Therefore, the quantity $P(F/C_i)$ is equal to 1, and the probability of failure is equal to the probability of the cause occurring, giving:

$$R = \prod_{i=1}^{n} \left[1 - P(C_i) \right] \tag{3}$$

(Note: Cases can exist when a cause of failure occurs without a failure occurring. For example, a cause of failure can occur in a redundant system without the system failing. Such cases are discussed in Chapter 11. For the purposes of this fundamental discussion, it is assumed that a failure always occurs when a cause exists.)

The quantity $P(C_i)$ can now be re-defined as the "unreliability" of the item with respect to failure cause C_i. Also substituting $P(F/C_i) = 1$ in expression (1), $[1 - P(C_i)] = R_i$, so that Expression (3) can be written:

$$R = \prod_{i=1}^{n} R_i \tag{4}$$

This expression can be interpreted as stating that the overall reliability of an item is equal to the product of the probabilities that the item will not fail due to any of the n possible causes of failure, given that if any "cause" exists, a failure will occur.

If the "causes" of system failure are interpreted as independent failures of physical elements of the sytem (i.e., subsystems, equipments, units, etc.), then R_i in expression (4) can be interpreted as the reliability of the i^{th} physical element of the system out of a total of n independent elements.

2.2 Reliability as a Function of Time

To this point, reliability has been considered simply as a probability of success (no failure). However, reliability has been defined with reference to a "specific period of time." Therefore, the expression (4) will be restated in terms of time as follows:

$$\boxed{R(t) = \prod_{i=1}^{n} R(t)_i} \tag{5}$$

where:

$R(t)$ = The probability that the system will not fail before time t. (In this case a "system" is considered to be any device consisting of n elements, none of which can fail without system failure.)

$R(t)_i$ = The probability that the i^{th} element of the system will not fail before time t.

This relationship between reliability and time provides the basic mathematical foundation of reliability prediction, and permits predictions to be based on measurable time-to-failure characteristics of system elements. The factor $R(t)_i$ will now be examined in more detail.

Let:

$R(t)_i =$ Probability of survival of element i over time t .

Then

$f(t)_i = \frac{dR(t)_i}{dt} \equiv$ The survival density function, i. e., the probability that a failure will not occur in the next time increment dt .

Now, $\frac{d[1 - R(t)_i]}{dt} = - \frac{dR(t)_i}{dt} = - f(t)_i \equiv$ The failure density function, i. e., the probability that a failure will occur in the next time increment dt.

Let:

$z(t)_i =$ The hazard rate, or the probability that a failure will occur in the next instant of time assuming previous survival, then:

$$z(t)_i = - \frac{f(t)_i}{R(t)_i} \qquad (6)$$

The quantity $z(t)_i$ can be defined as the hazard rate of element i at time t . In general, it can be assumed that the hazard rate of electronic elements remain constant over practical intervals of time, and that $z(t)_i = \lambda_i$ the constant, expected number of random failures per unit of operating time of the i^{th} element, i. e., the failure rate. Thus, when a constant failure rate can be assumed:

$$z(t)_i = \lambda_i = - \frac{f(t)_i}{R(t)_i} = - \frac{\frac{dR(t)_i}{dt}}{R(t)_i}$$

Solving this differential equation for $R(t)_i$ gives the exponential distribution function commonly used in reliability prediction:

$$\boxed{R(t)_i = e^{-\lambda_i t}} \tag{7}$$

Also, the mean time to failure can be determined by:

$$MTBF = \int_0^{\infty} R(t)\,dt.$$

so that, when a constant failure rate λ_i can be assumed:

$$\boxed{MTBF_i = \int_0^{\infty} e^{-\lambda_i t}\,dt = \frac{1}{\lambda_i}} \tag{8}$$

Expressions (7) and (8) are the basic mathematical relationships used in reliability prediction. It must be noted, however, that these expressions were derived based on the fundamental assumption that the failure rate of the item under consideration is a constant. When the failure rate is not constant, the more general hazard rate must be considered, in which case the element reliability is obtained using the more general expression:

$$R(t)_i = e^{-\int_0^{\infty} z(t)_i\,dt} \tag{9}$$

The emphasis on the exponential distribution in reliability work makes a discussion of the use of this function as a failure-probability model worthwhile. The mechanism underlying the exponential reliability function is that the hazard rate (or the conditional probability of failure in an interval, given survival at the beginning of the interval) is independent of the accumulated life.

The use of this type of "failure law" for complex systems is usually justified because of the many forces that can act upon the system and produce failure. For example, different deterioration mechanisms, different part hazard-rate functions,

and varying environmental conditions often result in effectively random system failures.

Another justification for assuming the exponential distribution in long-life complex systems is the so-called "approach to a stable state," wherein the system hazard rate is effectively constant regardless of the failure pattern of individual parts. This state results from the mixing of part ages when failed elements in the system are replaced or repaired. Over a period of time, the system hazard rate oscillates, but this cyclic movement diminishes in time and approaches a stable state with a constant hazard rate.

A third justification for assuming the exponential distribution is that the exponential can be used as an approximation of some other function over a particular interval of time for which the true hazard rate is essentially constant.

The preceding paragraphs are not intended to imply that the exponential assumption is generally valid. Because of its mathematical simplicity and the extensive theory developed by many researchers, the exponential density plays a prominent role in reliability work. However, if observed failure data do not support the exponential assumption, or if such factors as wear-out are expected to be significant, the exponential assumption can be erroneous. In such cases, other distributions, such as the lognormal, gamma and Weibull distributions are available for performing more valid predictions. These more complex situations will not be treated in this chapter. For information concerning the application of such techniques, the reader is directed to the references listed in Chapter 12. Also, some discussion of distribution other than exponential is presented in Chapter 10.

2.3 System Reliability-Element Reliability Relationships

Expressions (5), (7), and (8) are the most common basic expressions used as mathematical foundations of reliability prediction. This is partly because of the proportion of cases in which a constant hazard rate or failure rate can be assumed, and partly because of the relative simplicity with which exponential functions can be manipulated. This ease of manipulation is especially valuable when the total system, subsystem, or equipment reliability is being predicted as a function of the reliability of lower-level elements.

Consider the application of expression (5) in calculating the total reliability as a function of the reliabilities of individual elements. Substituting expression (7) for $R_i(t)$ gives:

$$R(t) = \prod_{i=1}^{n} e^{-\lambda_i t} = e^{-\lambda_1 t} \cdot e^{-\lambda_2 t} \cdots e^{-\lambda_n t}$$

This can be simplified:

$$R(t) = e^{-(\lambda_1 t + \lambda_2 t + \ldots + \lambda_n t)} = e^{-(\lambda_1 + \lambda_2 + \ldots + \lambda_n)t}$$

The general form of this expression can be written:

$$\boxed{R(t) = e^{-t\sum_{i=1}^{n} \lambda_i}} \qquad (10)$$

Another important relationship is obtained by considering the system failure rate (λ_s) to be equal to the sum of the individual failure rate of n independent elements of the system such that:

$$\lambda_s = \sum_{i=1}^{n} \lambda_i .$$

Revising expression (8) to refer to the system rather than an individual element gives the mean time between failures of the system as:

$$\boxed{MTBF = \frac{1}{\lambda_s} = \frac{1}{\sum_{i=1}^{n} \lambda_i}} \qquad (11)$$

3. PREDICTION TECHNIQUES

Typical reliability prediction techniques within each of the categories defined in paragraph 1.2 are described in subsequent paragraphs of this chapter. These techniques are also summarized in Tables IX-2 IX-3 and IX-4 with respect to factors that should be considered in selecting the most appropriate technique for a given application.

Table IX-2. Reliability Prediction Techniques Useful During Conception and Early Definition Phase

TECHNIQUE CATEGORIES	CHARACTERISTICS	ASSUMPTIONS	TYPICAL APPLICATIONS	RELATIVE ACCURACY[1]	RELATIVE LEVEL OF EFFORT REQUIRED[1,2,3]
Similar Equipment	Comparison of Equipment under consideration with similar equipment of known reliability.	Assumes orderly evolution of equipments and that similar equipments exhibit similar reliability.	Feasibility Studies Allocation Studies Proposal Evaluation	Ball Park estimation only. Suitable for weighing one approach against another.	Level 3 - 1 man-day
Similar Complexity	Estimation of equipment reliabiltiy as a function of the relative complexity of the subject item with respect to a "typical" item of similar type.	Assumes that a predictable correlation exists between complexity and reliability.	Feasibility Studies Allocation Studies Proposal Evaluation	Provides "infield" estimate when no new technology is involved.	Level 2 - 2 man-days
Prediction by Function	Considers operational function together with complexity in providing a gross prediction of reliability	Assumes that a predictable correlation exists between reliability and function as well as between reliability and complexity.	Feasibility Studies Allocation Studies Proposal Evaluation	Depends on accuracy of engineering judgement and how new equipment fits into envelope of previous data analysis. Extrapolation may be questionable.	Level 2 - 2 to 4 man days

1. Estimate based on data presented in report: Reliability Prediction and Demonstration for Airborne Electronics September 1967. Hughes Aircraft Company, Culver City California (Contract F30602-67-C-0221), RADC-TR-68-223.

2. Skill levels: Level 2 - engineer with appropriate specialized experience;
   Level 3 - senior technician level having ten years experience in reliability.

3. Relative time (man-days, etc.) is best engineering judgment estimate of relative time to obtain data, apply technique, and prepare report. Assumes typical system of moderate complexity. These values should be considered in their relative sense only.

Table IX-3 Reliability Prediction Techniques Useful During Definition and Acquisition Phase

TECHNIQUE CATEGORIES	CHARACTERISTICS	ASSUMPTIONS	TYPICAL APPLICATIONS	RELATIVE ACCURACY[1]	RELATIVE LEVEL OF EFFORT REQUIRED[1,2,3]
Part Count Prediction	Considers average failure rates of various classes or types of parts together with quantities of parts of each class or type in the equipment.	Average stress levels in new design are assumed to approximate average levels of stress in previous designs. Also, nominal levels of environmental stress are assumed. Math model assumed exponential.	Design Comparison Proposal Evaluation Trade Studies Design Review Design Analysis (Preliminary)	If model assumption is correct and failure rates accurate a close approximation of MTBF will result.	Levels 1 and 2- 0.6 man weeks
Stress Analysis Prediction	Considers part type, operational and environmental stresses and derating characteristics associated with each individual part in predicting MTBF.	Assumes exponential distribution of part failure. Assumes that similar parts operated under similar conditions will exhibit comparable reliability.	Design Review Trade Studies Design Analysis	If model assumption is correct and stresses accurately determined, a good approximation of MTBF will result.	Levels 1 and 2 3 man weeks to 1.5 man months.

1. Estimate based on data presented in report: Reliability Prediction and Demonstration for Airborne Electronics, Sept. 1967, Hughes Aircraft Company, Culver City, California. (Contract F30602-67-C-0221.) RADC-TR-68-223.

2. Skill levels: Level 1 - Senior engineer with over 10 years related experience.
   Level 2 - Engineer with appropriate specialized experience.

3. Relative time (man-weeks, etc.) is best engineering judgement of relative time to obtain data, apply technique, and prepare report. Assumes typical system of moderate complexity. These values should be considered in their relative sense only.

Table IX-[illegible] Reliability Prediction Techniques Useful During Detailed Design Stages of Acquisition Phase

TECHNIQUE	CHARACTERISTICS	UNIQUE REQUIREMENTS AND ASSUMPTIONS	TYPICAL APPLICATIONS	RELATIVE ACCURACY[1]	RELATIVE LEVEL OF EFFORT[1,2,3]
Degradation Analysis	Computer implemented circuit analysis technique utilized in evaluating and optimizing reliability design. Includes four general methods as follows:	All methods require a mathematical model in the form of circuit equations.		Accuracy depends on accuracy of mathematical model and input data.	All methods involve extensive modeling effort at Levels 1 to 3.
. Parameter Variation Methods	Computer program varies input parameters 1 or 2 at a time in pre-determined discrete step.	Requires nominal value of each input parameter	Design Analysis Trade Studies	Provides good measure of sensitivity of output to input parameter variation	Levels 1 2 and 3 1 man month
. Worst-Case Methods	Computer program varies all input parameters in direction of degrading output variable until worst value of each parameter is reached. Worst case output variables then defined.	Requires nominal value and tolerance or end-of-life limits for each part or input parameter.	Design Analysis (Failure mode and effect analyses, etc.) Trade Studies	Good measure of relationship of output to expected variations of input parameters.	Levels 1, 2 and 3 2 man months
. Moment Methods	Computer program uses part parameter mean values, variance and parameter correlations to generate output variable means and variance.	Requires mean and variance of each input parameter, and correlation coefficients of related parameters. Assumes normal distribution of input parameters.	Design Analysis (Component drift effects, design optimization, etc.)	If model assumptions and input data are accurate a close estimate of drift characteristics will result. However, MTBF's not directly obtained.	Levels 1, 2 and 3 3 man months
. Monte Carlo Methods	Computer program simulates statistical analysis of empirical data by iterative random selection of input parameter values from representative distributions	Requires complete statistical distribution of each input parameter.	Design Analysis (Component drift, FMEA, Design Optimization, etc.)	If model assumptions and frequency distributions are correct, a close approximation of output variable frequency distribution will result. Also gives good approx of drift characteristics.	Level 1, 2 and 3 3 man months plus input data analysis time to establish frequency distribution

1. Estimates based on data in report: Reliability Prediction and Demonstration for Airborne Electronics, Sept. 1967, Hughes Aircraft Co. Culver City, Calif. (Contract F30602-67-C-0221), and on engineering judgment

2. Skill Levels: Level 1 - Senior Engineer with over 10 years related experience
   Level 2 - Engineer with appropriate specialized experience
   Level 3 - Senior technician level having ten years experience in reliability.

3. Related time (man-months) is best engineering judgement of relative time to obtain data, develop model, apply technique and prepare report. Assumes a typical system of moderate complexity. These values should be considered in their relative sense only.

Table IX-2 summarizes those techniques that are of most value to Air Force reliability specialists in performing feasibility and allocation studies during the Conceptual and early Definition Phases. Table IX-3 summarizes more detailed techniques that are commonly used by contractors in performing allocations and trade-off's during the Definition Phase, and in preparing input to design reviews during the Acquisition Phase. These techniques are also used by the SPO in comparing alternate designs and evaluating proposals. The techniques summarized in Table IX-4 are relatively complex and expensive in application, and are usually used by contractors in performing critical design analyses and trade-off studies during the detailed engineering activities of the Acquisition Phase.

4. SIMILAR EQUIPMENT TECHNIQUES

Several techniques have been developed and used in performing very early predictions of equipment reliability before any characteristics of the system design have been established. The most basic of these techniques involve a simple estimate of equipment reliability in terms of MTBF, failure rate, or similar parameters, based on experience gained from operational equipments of similar function.

In general, these similar equipment prediction techniques involve the following steps:

a. Defining the new equipment in terms such as general equipment type (e.g., radar), operational use (e.g., ground based) and other known characteristics.

b. Identifying an existing equipment or class of equipments that most nearly compares with the new equipment.

c. Obtaining and analyzing historical data generated during operation of the existing equipment to determine, as nearly as possible, the reliability of the equipment under the stated operating environment.

d. Drawing conclusions concerning the level of reliability that will be demonstrated by the new equipment. Such conclusions assume that similar equipment will exhibit similar reliability, and that reliability achievement evolves in an orderly manner from one generation of equipments to the next. These reliability prediction techniques permit very early estimation of the failure rate of a new equipment based on experience gained from operational equipments of similar function. The accuracy of the estimates, however, depends on the quality of historical data, and the similarity between the existing and new equipments.

Obviously, more meaningful and accurate results are achieved if a technique based on field results of similar products is used. Also, other factors such as design practices, and production techniques are more likely to be similar to those on past equipments designed and built by the same manufacturer than those of another manufacturer.

In most cases, prediction techniques such as this are used in estimating the feasibility of meeting some minimum reliability objective within the constraints of the current state-of-the-art.

5. SIMILAR COMPLEXITY TECHNIQUES

Several techniques are available for performing reliability predictions based on the complexity of the equipment of interest. These techniques have been developed as a result of analyses that indicate a direct and predictable correlation between equipment complexity and reliability. However, such predictions are complicated, somewhat, by the influence of the equipment type or different environments in which the equipment will be operated. Therefore, methods for predicting reliability as a function of equipment complexity include provisions for compensating for use environment factors.

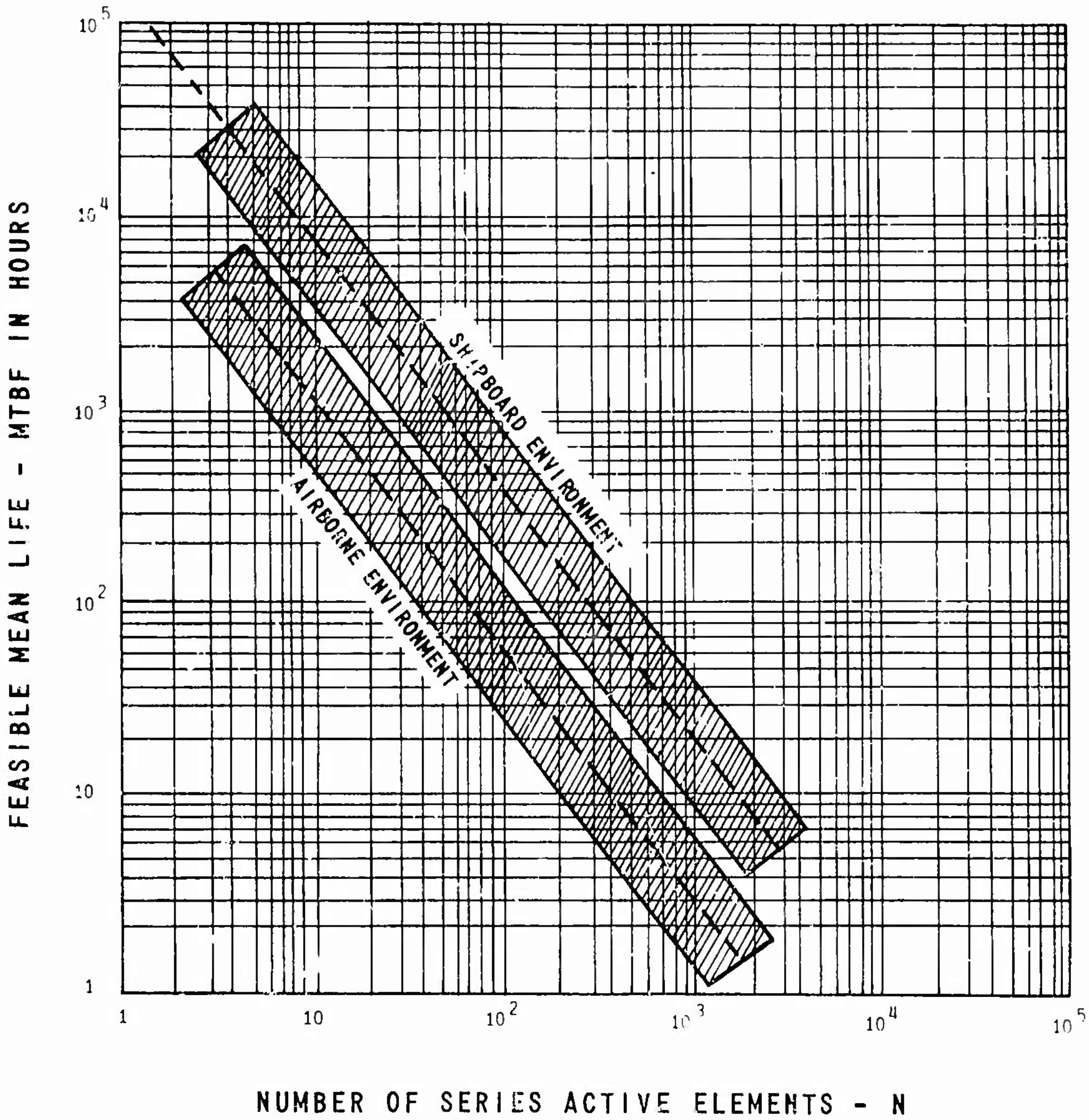
The most commonly used similar complexity techniques involve the use of graphical procedures relating failure rate to active element group count and use environment. Two representative examples of such techniques are described below.

5.1 MIL-STD-756A AEG Method

A graphical device for relating reliability to electronic equipment complexity is provided in MIL-STD-756A. Application of the procedure involves estimating the number of active element groups (AEG's) in each functional block of the equipment. An active element is defined as an electron tube or transistor, except that ten computer diodes and associated circuitry are considered as an active element in digital computers. This graph should not be used for equipment containing integrated circuits.

The graph published in MIL-STD-756A for determining reliability in terms of feasible mean life or MTBF is reproduced in Figure 9-1 This graph includes two bands indicating the probable range of achievable reliability for equipments to be operated in airborne and shipboard environments. The higher MTBF values for a given number of series active elements represent the level of reliability that can be achieved with good reliability engineering and design effort.

The reliability estimate obtained from this chart represents a band of possible outcomes. The smaller failure rate values of the band are obtainable with good reliability engineering and design effort.



(Reproduced from MIL-STD-756A)

Figure 9-1 MTBF Versus Functional Complexity for Electronic Equipment

5.2 Bird Engineering-Research Associates Method

Devices similar to the MIL-STD-756A AEG method described in paragraph 5.1 have been developed for other operational environments, and are available in a variety of sources. Two of these, as developed by Bird Engineering-Research Associated, Inc., are presented in Figures 9-2 and 9-3.[1] Procedures for using these methods are essentially the same as for the MIL-STD-756A method. However, the source document also describes the following procedure for estimating functional complexities (number of AEG's in an equipment function). These procedures do not apply for equipments containing integrated circuits.

Functional complexity is related to the number of series "active" elements (transistors, diodes, tubes, etc.) to be used in the subsystem. Detailed schematics for the new design are normally not available in the early stages of system planning. It may be necessary, therefore, to estimate complexity of the electronic subsystem on the basis of previous designs of comparable functional complexity and performance requirements.

Table IX-5 tabulates the range of series complexity (in AEG's) in which predecessor designs have fallen. In the absence of a better estimate of AEG complexity for specific functional blocks within the particular subsystem under study, an estimate may be derived from the table for preliminary feasibility estimation.

In those instances in which logic diagrams and circuit schematics are available for certain blocks of the functional block diagram, the AEG density per block is estimated by making an actual count of the active elements. When the subsystem under consideration is predominantly analog in function and is comprised of 200 or more active element groups of all types, it is permissible to give all AEG's equal weight - i.e., 1 AEG = 1.0 unit of complexity. However, if an estimate of AEG complexity is to be made on a component-by-component basis, where individual component complexities are considerably less than 200, a more realistic appraisal of functional complexity is obtained by applying a weighting factor to each class of active elements in the component. A list of "relative" weighting factors applicable to electronic components is shown in Table IX-6.

Once the complexities have been estimated, the nomograph of Figure 9-2 can be used to estimate average failure rates as a function of complexity within analog subsystems, to account for catastrophic as well as tolerance and interaction failures. The following rules and assumptions apply to analyses made at the subsystem level:

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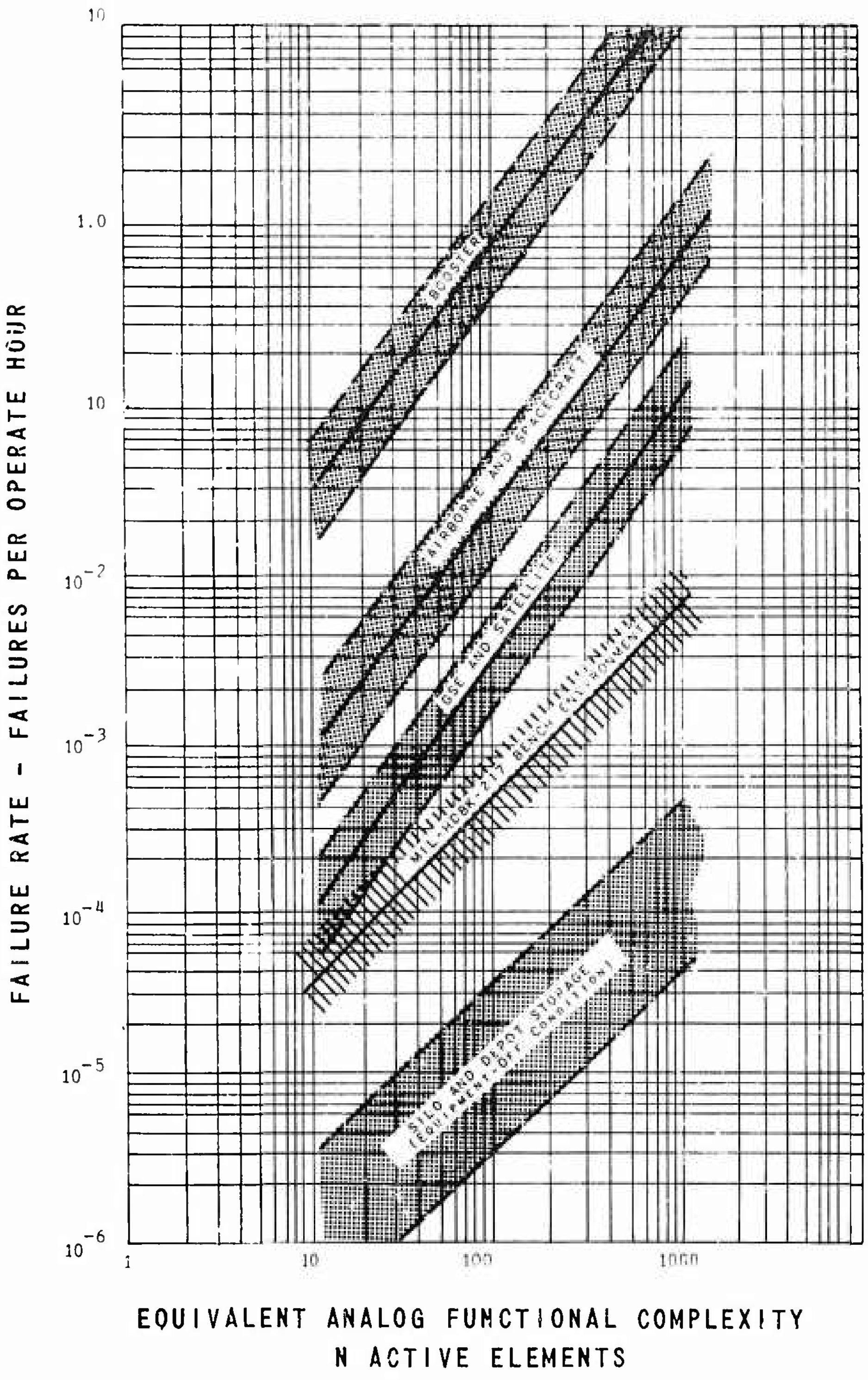
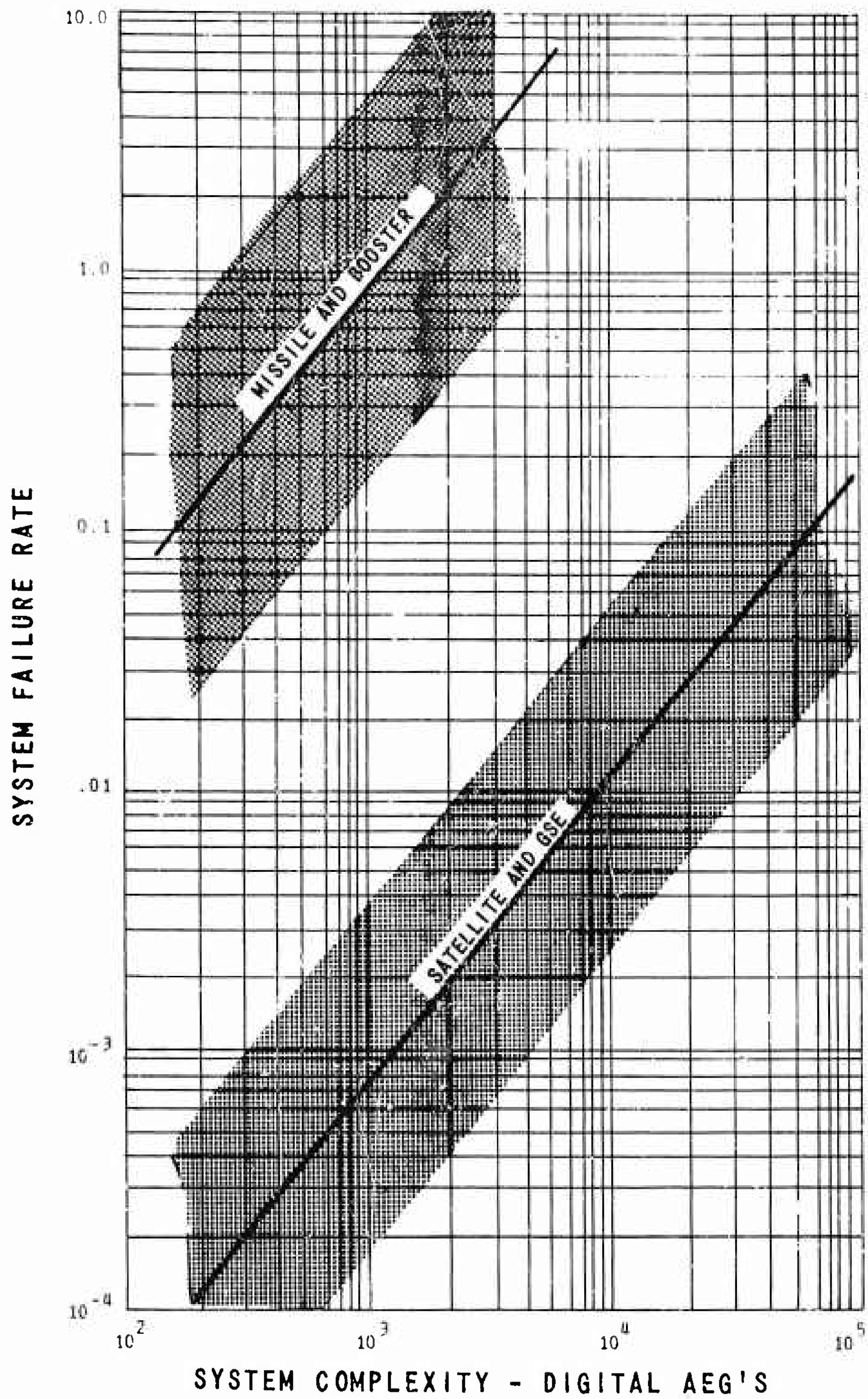
[1] Handbook of Reliability Prediction Procedures for Ballistic and Space Systems, Bird Engineering-Research Associates, Inc., Vienna, Va, DDC No. AD470294.



(Reproduced from Handbook of Reliability Prediction Procedures for Ballistic and Space Systems, Bird Engineering-Research Associates, Inc., DDC No. AD470294)

Figure 9-2. Reliability Feasibility Estimation Nomograph for Analog Electronic Functions



(Reproduced from Handbook of Reliability Prediction Procedures for Ballistic and Space Systems, Bird Engineering-Research Associates, Inc. DDC No. AD470294

Figure 9-3. Reliability Feasibility Estimation Nomograph for Digital Electronic Functions

Table IX-5. AEG Complexities Required for the Performance of Specific Electronic/ Electrical Subsystem Functions in Ballistic and Space Systems

Subsystem and Function	Analog* AEG Range	
	Minimum	Maximum
Guidance and Control:		
Command Receiver (basic)	30	100
Guidance Computer (digital)	500 (d)	1500 (d)
Programmer Logic & Switching (digital)	50 (d)	250 (d)
Signal Processor	2	10
Analog Servo Amplifier	4	10
Inertial Reference Platform	50	300
Horizon Sensor	20	100
Star Tracker	20	100
Gyro Package	10	50
Electrical System:		
Battery Supply & Temp. Control Ckts	10	50
DC/AC Inverter, Single-Phase	20	50
DC/AC Inverter, 3-Phase	40	100
AC/DC Converter/Regulator	5	20
Telemetry:		
Transmitter	10	30
Modulator	5	50
Signal Processor (per channel)	5	10
Sensor/Amplifier	2	5
Receiver	20	60
Beacon Transponder	40	100
Arming and Fuzing	20	200
Sense/Switch Device (for redundant designs)	5	50

*All values are equivalent analog AEG's for use with Figure 9-2 except those denoted by (d) which should be used with Figure 9-3.

Table IX-6. Weighting Factors for Estimating Equivalent Analog Complexity of Electronic Subsystems (for Use With Figure 9-2)

AEG Type	Function	Equivalent Analog AEG,s
Transistor or Electron Tube	Signal-level analog function Signal-level digital function Power conversion and regulation	1.0 0.1
Diodes	Signal-level analog function Signal-level digital function	0.1 0.01
Microwave Power Tubes	Traveling wave tubes, magnetrons, klystrons	100.0
Photo-Electric Cell	Light sensor functions	0.1
Photo Multiplier	Light amplifier	10.0
Solar Cell	Power generation	0.01
Relays	General	1.0
Gyros, Position	Inertial reference	50.0*
Gyros, Rate	"Rate" signal	10.0*
Accelerometers	Acceleration measurement	1.0
Crystals	Frequency determination	1.0

*For short-duration missions -- e.g., ballistic flight and space flights of less than 500 hours.

a. A power subsystem of a given complexity is assigned an AEG failure rate twice that of an AEG in an analog subsystem of the same complexity.

b. The number of digital AEG's in an analog subsystem should be divided by ten if only the analog AEG chart (Figure 9 -2) is used for subsystem failure-rate estimation.

For digital AEG's in a digital system - e.g., computers - the nomograph presented in Figure 9-3 should be used. This family of nomographs relates failure rate of digital computer functions to series complexity of the digital system. Digital system failure-rate estimates made on the basis of these nomographs usually fall within +200% and -67% of the values actually observed in the field. Digital system failure-rate estimates must be considered tentative until verified by test.

6. PREDICTION BY FUNCTION TECHNIQUES

Recently, several techniques have been developed which permit the prediction of equipment or system reliability with relation to the functional characteristics of the equipment, as opposed to complexity or part stress/population techniques normally employed. These techniques are based on correlations between significant functional characteristics and observed operational reliability. These techniques are not intended to replace conventional methods of reliability prediction, but rather supplement these techniques by permitting reliability predictions during early phases of a design cycle when data concerning part application are not available.

Three typical reliability prediction by function techniques are described below. For the purpose of this notebook, these techniques will be identified as follows:

a. FEC Ground Equipment Method. This technique is described in Technical Report No. RADC-TR-65-27, System Reliability Prediction By Function, May 196[illegible] DDC No. AD466025.

b. ARINC Ground Equipment Method. This technique is described in Technical Report No. RADC-TR-63-300, System Reliability Prediction By Function, which includes:

Volume I - Development of Prediction Techniques, DDC No. AD416494

Volume II - Prediction Procedure, DDC No. AD418192 Supplement 1, Revised Equations, DDC No. AD614227

c. ARINC Airborne Equipment Method. This technique is described in Technical Report No. RADC-TR-66-509, Avionics Reliability and Maintainability Prediction by Function. DDD No. AD802998.

6.1 FEC Ground Equipment Method

This technique makes use of a set of equations and equivalent graphs relating to ground-based equipment function (e.g., receiver, transmitter, etc.) and a major operational characteristic of that function (e.g., noise figure, peak power, etc.) to a predicted value of MTBF or failure rate. The total system reliability can be estimated by appropriately combining individual function reliabilities.

Predictions are performed as follows:

a. Identify the equipment according to one of the following general functions as most applicable:

- Radar Receiver/Transmitter
- Radar Display
- Radar Receiver
- Radar Transmitter
- Communications Receiver
- Communications Transmitter
- Communication Multiplex
- EDP Central Processor
- EDP Peripheral Equipment

b. Determine values of key parameters associated with equipment in question. Key parameters are identified in Table IX-7 for respective equipment functions.

c. Determine the equipment MTBF or Failure Rate using either the equations presented in Table IX-7, or the referenced graphs as appropriate.

Table IX-7. Parameters and Equations For FEC Prediction By Function Technique.

Equipment Function	Key Parameters	Reliability Measure	Equations	Graphs
Radar Receiver/ Transmitter	P_p = Radar system peak power output in kilowatts. A_{RT} = Number of active element groups in rec/trans.	λ_{RT} = Receiver/transmitter failure rate in failures per 10^6 hours.	$\lambda_{RT} = 6.3\,A_{RT}(P_p)^{0.30}$	Figure 9-4
Radar Display	τ = Maximum pulse width in microseconds.	$MTBF_D$ = Display MTBF in hours. λ_D = Display failure rate in failure per 10^6 hours.	$MTBF_D = 1483 + 3314 \cdot \log_{10}\tau$. $\lambda_D = \frac{10^6}{MTBF_D}$	Figure 9-5
Radar System (Receiver/Transmitter plus display)	λ_{RT} = Receiver/transmitter failure rate in failures per 10^6 hours. λ_D = Display failure rate in failures per 10^6 hours.	λ_{RTD} = System failure rate in failure per 10^6 hours. $MTBF_{RTD}$ = System MTBF in hours.	$\lambda_{RTD} = \lambda_{RT} + \lambda_D$ $MTBF_{RTD} = \frac{10^6}{\lambda_{RTD}}$	
Radar Receiver	P_p = Radar system peak power output in kilowatts. A_R = Number of active element groups in receiver.	λ_R = Receiver failure rate in failures per 10^6 hours.	$\lambda_R = 4.17\,A_R(P_p)^{.32}$	Figure 9-6
Radar Transmitter	P_p = Radar system peak power output in kilowatts. A_T = Number of active element groups in transmitter.	λ_T = Transmitter failure rate in failures per 10^6 hours.	$\lambda_T = 9.06\,A_T(P_p)^{.36}$	Figure 9-7

Table IX-7 Continued

Equipment Function	Key Parameters	Reliability Measure	Equations	Graphs
Communications Receiver	N_F = Maximum Receiver Noise Figure in db.	$MTBF_R$ = Receiver MTBF in hours. λ_R = Receiver failure rate in failures per 10^6 hours.	$MTBF_R = (2889)e^{-.136N_F}$ $\lambda_R = \frac{10^6}{MTBF_R}$	Figure 9-8
Communications Transmitter	G = Transmitter power gain in db.	$MTBF_T$ = Transmitter MTBF in hours. λ_T = Transmitter failure rate in failures per 10^6 hours.	$MTBF_T = (6769)G^{-.624}$ $\lambda_T = \frac{10^6}{MTBF_T}$	Figure 9-9
Communications Multiplex	C = Total number of voice channels, including voice channels used for telegraph.	$MTBF_M$ = Multiplex MTBF in hours. λ_M = Multiplex failure rate in failures per 10^6 hours.	$MTBF_M = (783)e^{-.0178C}$	Figure 9-10
Communications System (Simplex System including 1 receiver, 1 transmitter and 1 multiplex.	λ_R = Receiver failure rate λ_T = Transmitter failure rate. λ_M = Multiplex failure rate.	λ_S = System failure rate in failures per 10^6 hours. $MTBF_S$ = System MTBF in hours.	$\lambda_S = \lambda_R + \lambda_T + \lambda_M$ $MTBF_S = \frac{10^6}{\lambda_S}$	

Table IX-7 Continued

Equipment Function	Key Parameters	Reliability Measure	Equations	Graphs
EDP Central Processor	W = Word size in bits. A = Add time (time for one addition plus obtaining stored data) in micro-seconds.	$MTBF_{CP}$ = Central Processor MTBF in hours. λ_{CP} = Central processor failure rate in failure per 10^6 hours.	$MTBF_{CP} = (524)e^{-.135W/A}$ $\lambda_{CP} = \frac{10^6}{MTBF_{CP}}$	Figure 9-11
EDP Peripheral Equipment	Equipment type or category.			Table 9-8

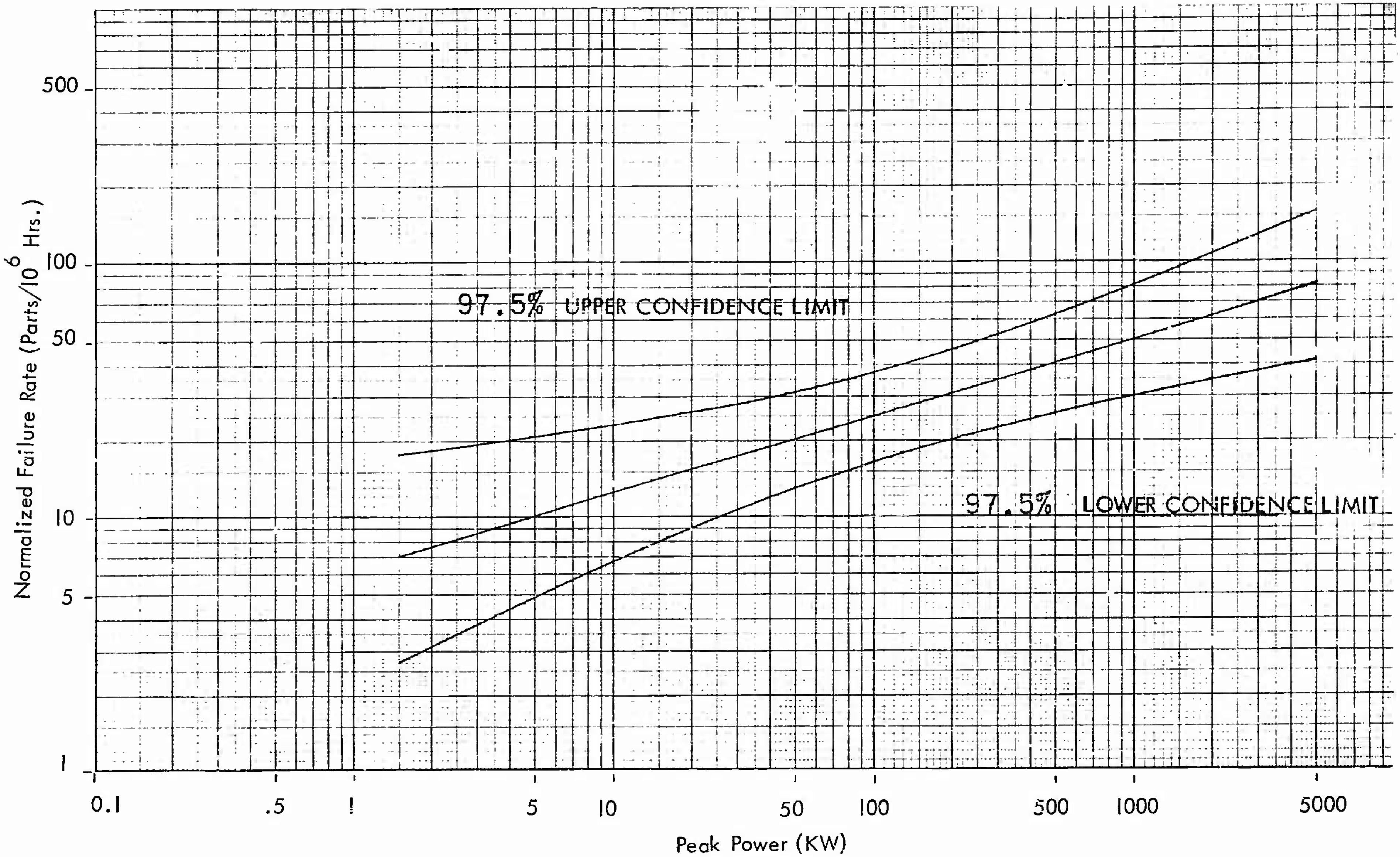


FIGURE 9-4 RADAR RECEIVER - TRANSMITTER FUNCTION - NORMALIZED FAILURE RATE VS. PEAK POWER

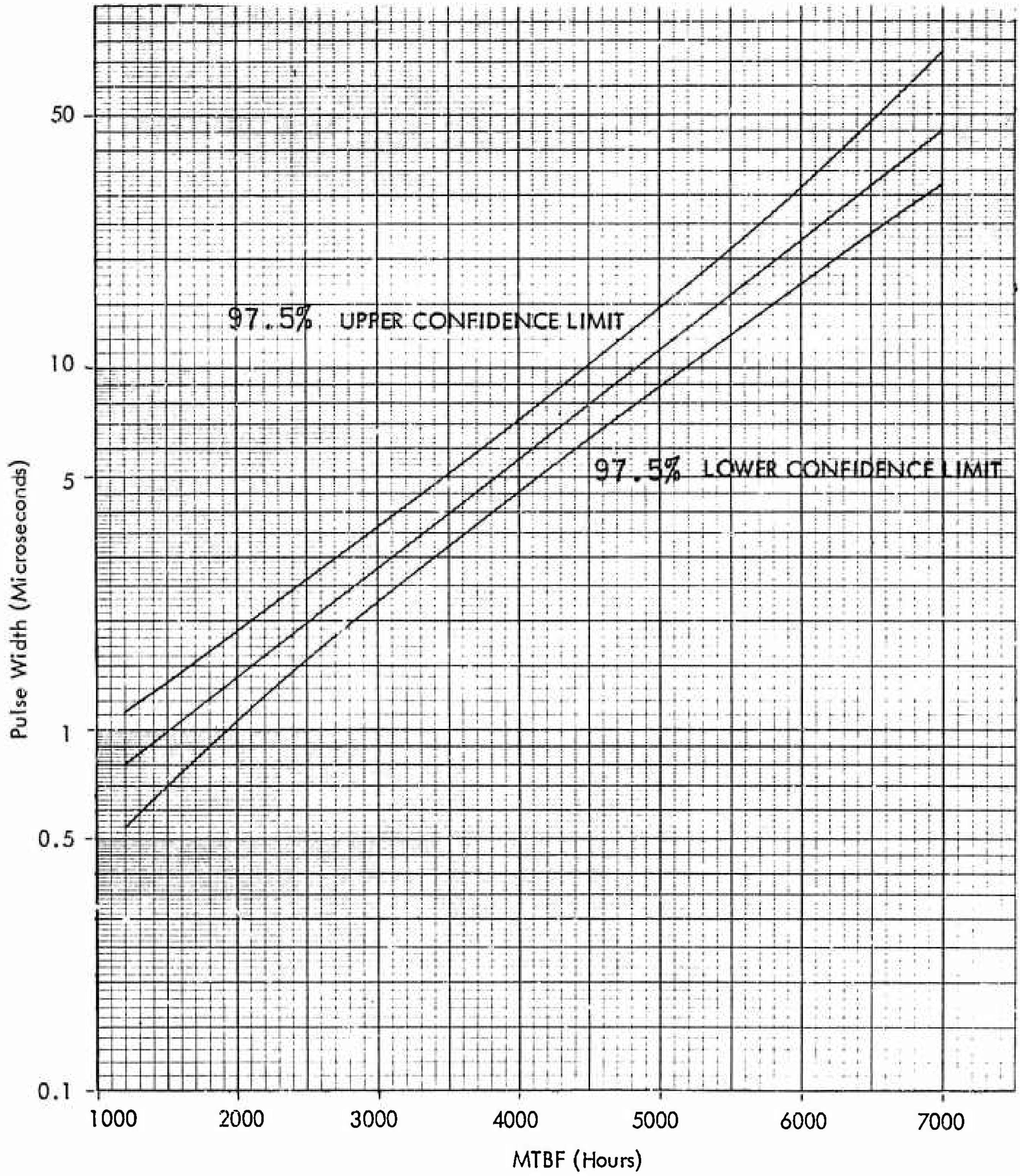


FIGURE 9-5 RADAR DISPLAY FUNCTION - PULSE WIDTH VS. MTBF

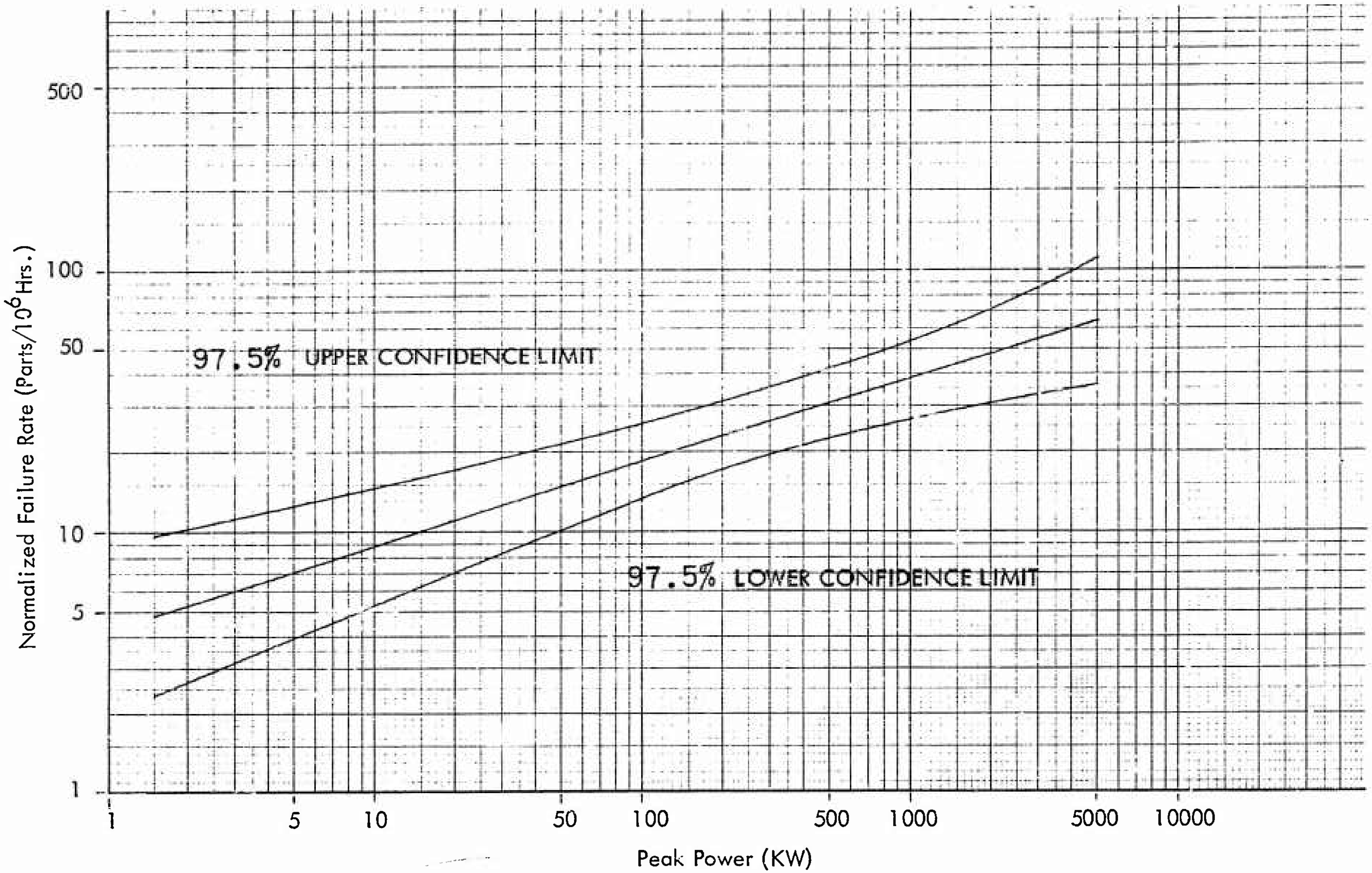


FIGURE 9-6 RADAR RECEIVER FUNCTION - NORMALIZED FAILURE RATE VS. PEAK POWER

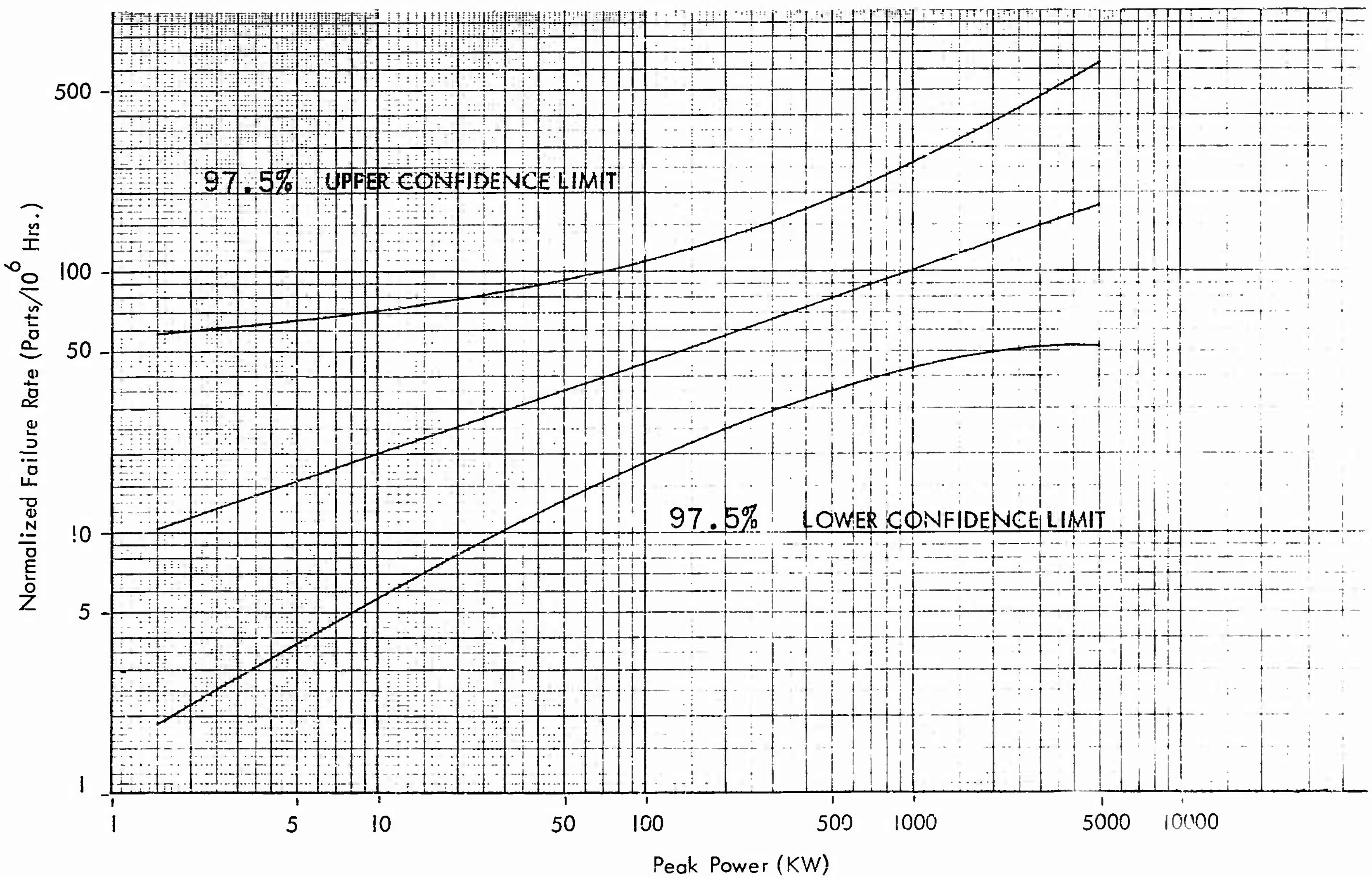


FIGURE 9-7 RADAR TRANSMITTER FUNCTION - NORMALIZED FAILURE RATE VS. PEAK POWER

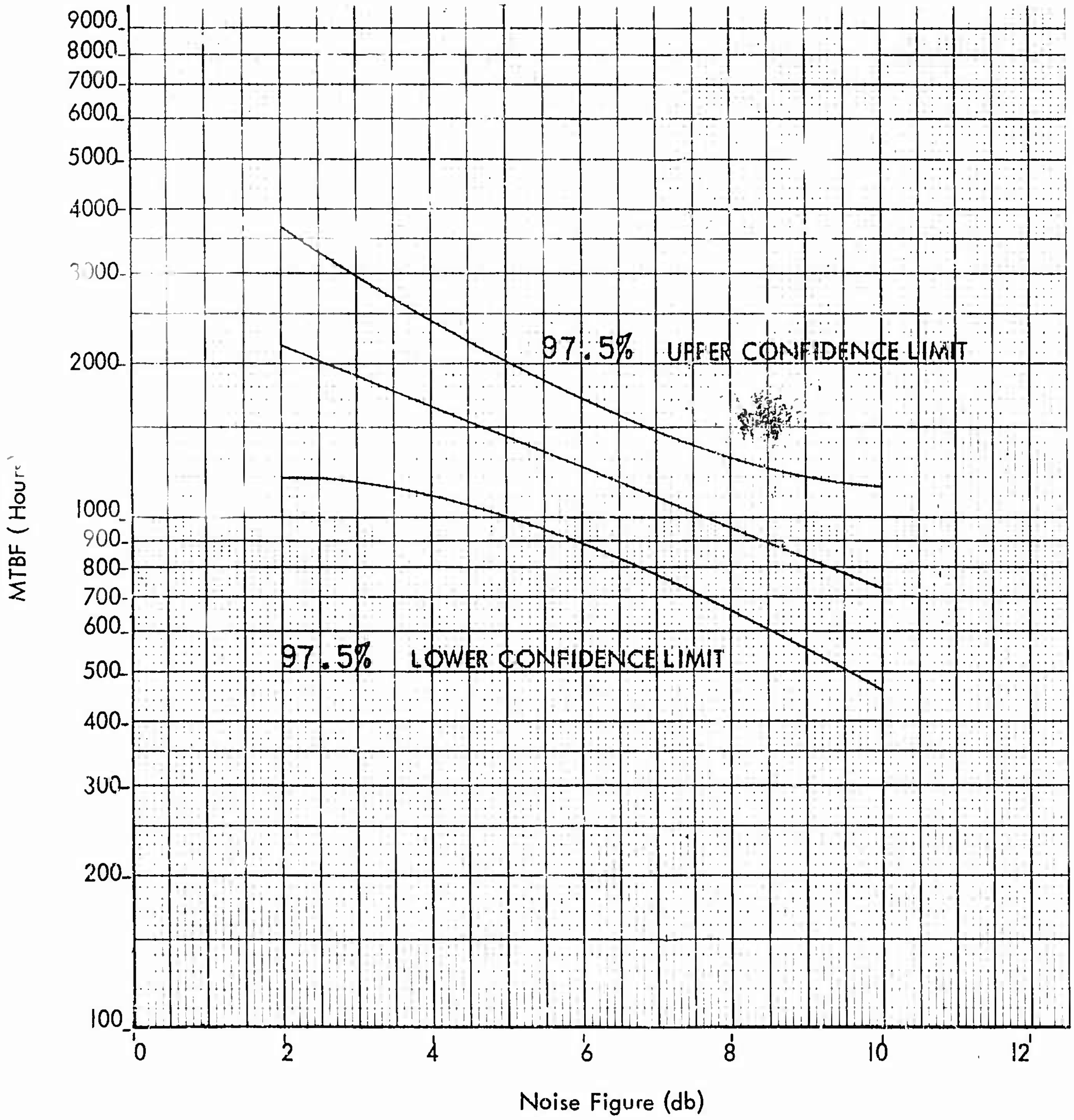


FIGURE 9–8 COMMUNICATION RECEIVER FUNCTION - MTBF VS. NOISE FIGURE

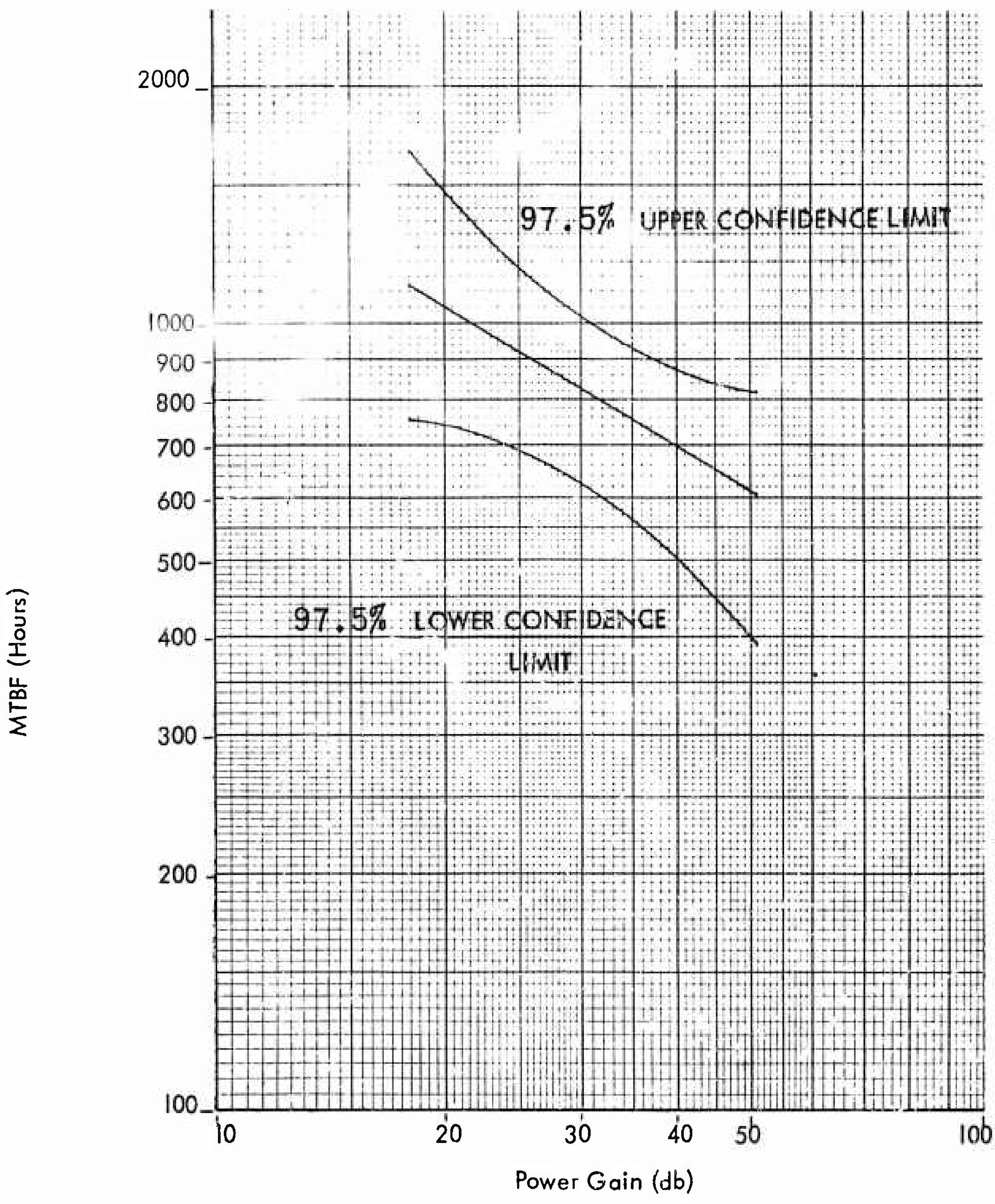


FIGURE 9-9 COMMUNICATION TRANSMITTER FUNCTION-
MTBF VS. POWER GAIN

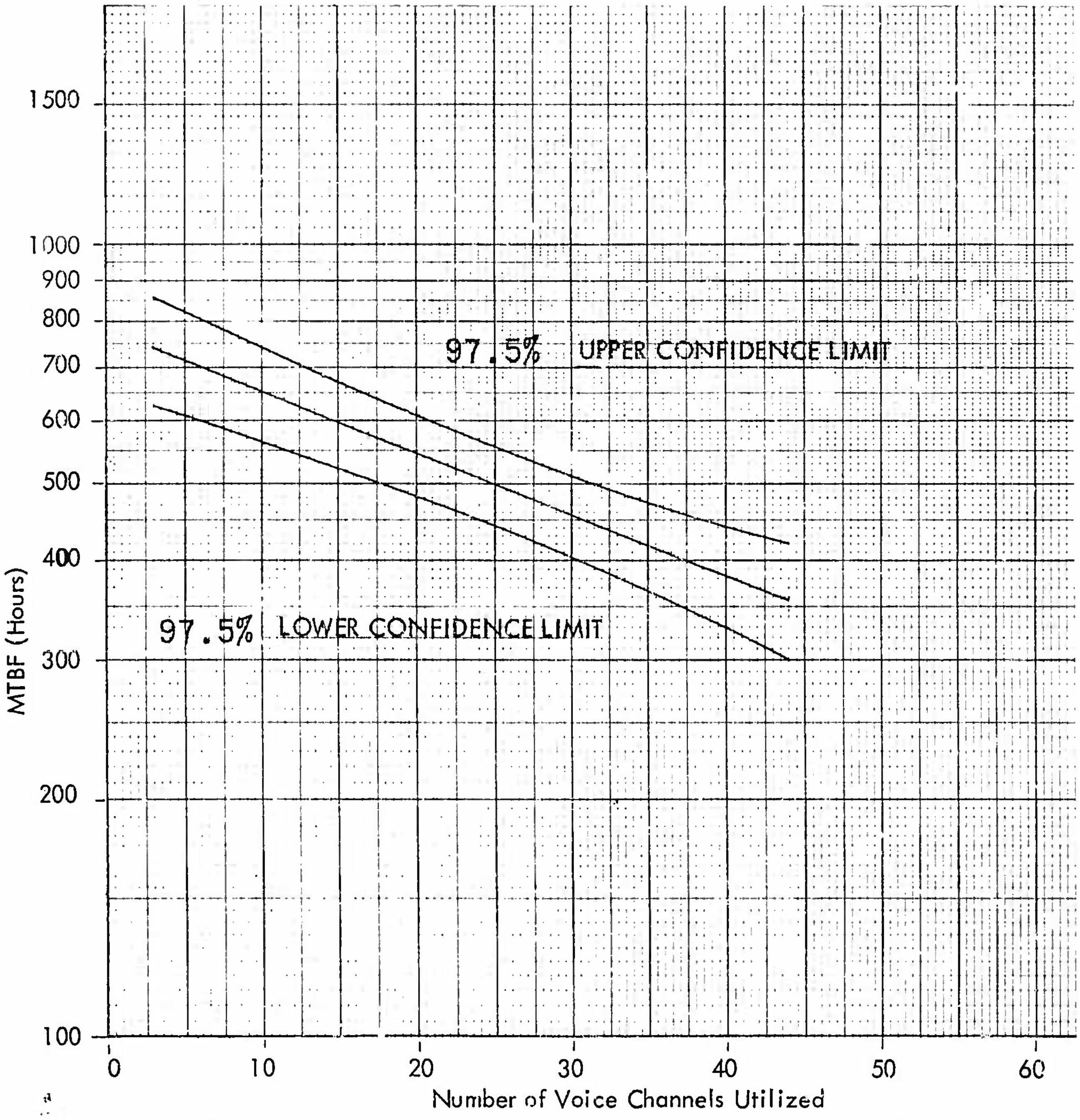


FIGURE 9-10 COMMUNICATION MULTIPLEX FUNCTION - MTBF VS. NUMBER OF VOICE CHANNELS UTILIZED

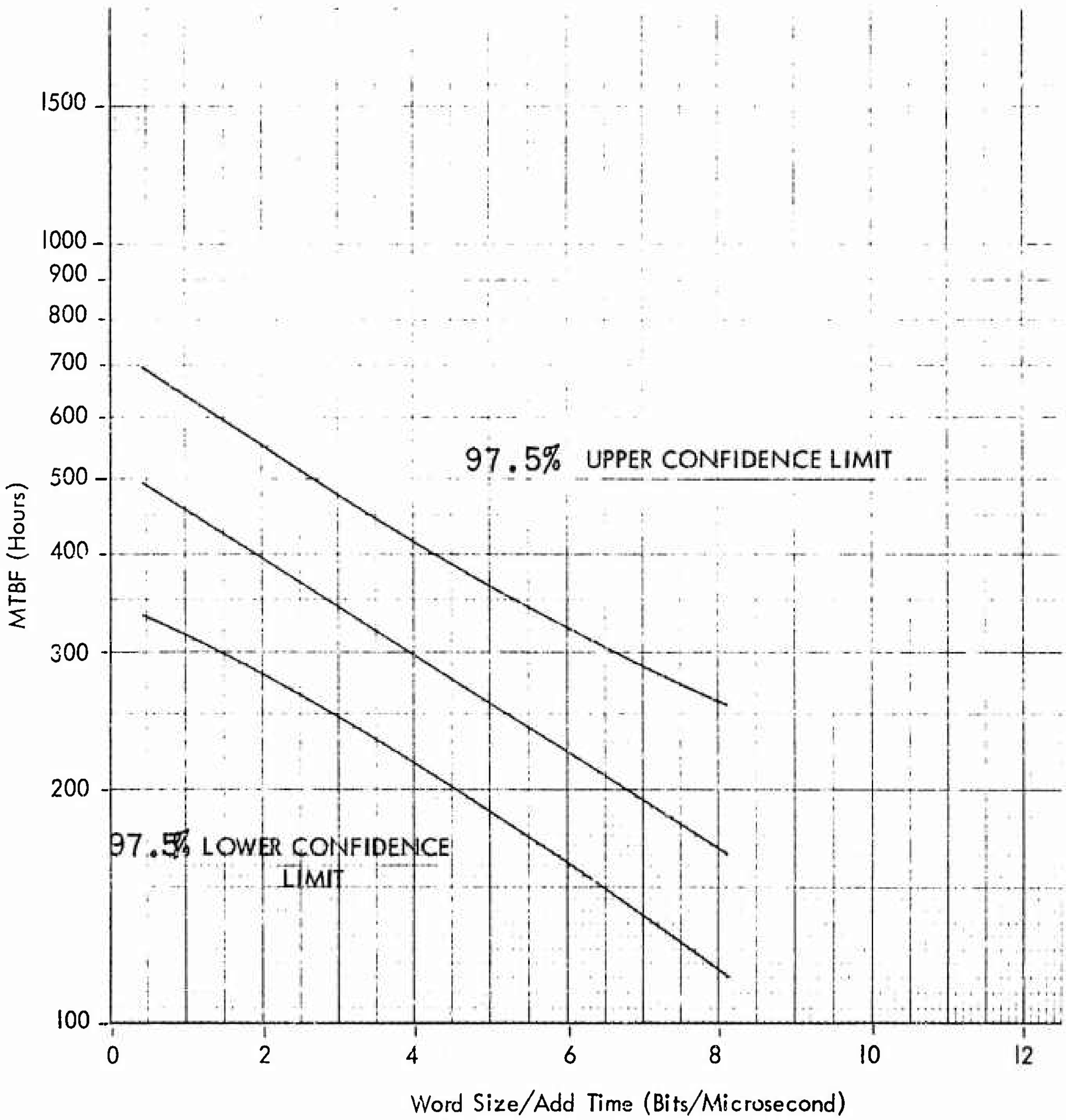


FIGURE 9-11 EDP CENTRAL PROCESSOR FUNCTION - MTBF VS. WORD SIZE/ADD TIME

Table IX-8. Reliability Data For EDP Peripheral Equipment*

Function	Type	Failure Rate (Failure Per 10^6 hours)	95% Confidence Band Around Failure Rate
Input	Paper Tape Reader	113	37-278
Output	Paper Tape Punch	136	50-297
	Typewriter	779	389-1394
	Print Unit	3413	2662-4326
Input/Output	Magnetic Tape Drive	786	710-866
	Typewriter	446	289-560
Auxiliary Storage	Drum	2137	1630-2754
Buffer	Tape Control Unit	976	794-1192

*Regression equations for EDP peripheral equipment could not be developed. These point-values for typical equipments can be used where appropriate. If other peripheral equipment are used, reliability data should be obtained from other sources.

d. When appropriate, determine system MTBF by combining equipment MTBFs or failure rates as indicated in Table IX-7.

6.2 ARINC Ground Equipment Method

This technique utilizes a set of "prediction equations" relating mean time between failure (MTBF) to the simultaneous influences of a variety of parameters characterizing the equipment of interest Predictions are performed as follows:

a. A prediction equation is selected such that the associated prediction parameters most nearly correspond to the characteristics of the equipment under consideration. The equations and the respective prediction parameters are listed in Table IX-9.

b. Prediction parameters for the selected equation are quantified in accordance with the instructions in Table IX-10.

c. The prediction equation is solved using these parameter values. Initial solution of the equation provides a predicted value of Ln $\hat{\theta}$, where $\hat{\theta}$ is the predicted mean time between failures. The predicted $\hat{\theta}$ can then be determined from the expression.

$$\hat{\theta} = e^{\mathrm{Ln}\,\hat{\theta}}$$

d. The confidence intervals of the predicted values are computed using the worksheets in Figures 9-12, 9-13, or 9-14. The worksheet selected should correspond to the particular prediction equation used. The approximate 95% confidence interval around the predicted value of $\hat{\theta}$ is given by:

$$\frac{\hat{\theta}}{g} \leq \hat{\theta} \leq \hat{\theta} g$$

where $g = e^{K}$, and K is calculated using the worksheet.

6.3 ARINC Airborne Equipment Methods

This technique is basically an extension of the ARINC Ground Equipment Method described in paragraph 6.2 to permit prediction of avionics equipment reliability. This technique is somewhat more comprehensive in scope, and permits consideration of the function of the line replaceable unit (LRU).

Table IX-9 Ground Equipment Reliability Prediction Equations

SYSTEM RESTRICTIONS	EQUATION DESIGNATION	EQUATION	PARAMETERS (See Table IX-10)
NONE	A	$\text{Ln}\ \hat{\theta} = 8.6859 - 0.5632\ X_a - 0.2556\ X_b - 0.0858\ X_c$ Standard Error of Estimate: $S = 0.400$	$X_a = \text{Ln}\ C$ (complexity) $X_b = \text{Ln}\ P$ (power consumption) $X_c = R$ (number CRT's)
RF Radiating System	B	$\text{Ln}\ \hat{\theta} = 6.4408 - 0.2055\ X_b - 0.5120\ X_d - 0.1597\ X_c$ Standard Error of Estimate: $S = 0.427$	$X_b = \text{Ln}\ P$ (power consumption) $X_d = \text{Ln}\ V$ (max DC voltage) $X_c = R$ (number CRT's)
Systems not Applicable for Eq. B. (i.e., non-radiating systems)	C	$\text{Ln}\ \hat{\theta} = 7.2612 - 0.5089\ X_d - 0.1123\ X_e$ Standard Error of Estimate: $S = 0.460$	$X_d = \text{Ln}\ V$ (max DC voltage) $X_e = \text{Ln}\ F$ (frequency)

Table IX-10. Prediction Parameters

Parameter	Definition	Quantification of Parameter	Range of Validity
Complexity (C)	Complexity is measured in terms of an adjusted active element count. A worksheet would be valuable in aiding in the numerical evaluation of this parameter. The number of each type of active element in the systems of this study ranged from zero to the following maxima: Tubes -- 3,037 Analog transistors -- 4,167 Solid state power rectifiers -- 204 Digital diodes -- 25,000 Digital transistors -- 3,083 Analog diodes -- 692 An element is considered as digital in application if the function depends primarily on the existence of a pulse, rather than on the shape or amplitude of a signal.	Ln C C=1.0 x No. of electron tubes (all types) +0.3 x No. of analog transistors +0.4 x No. of solid state power rectifiers +0.006 x No. of solid state digital diodes +0.02 x No. of digital transistors +0.1 x No. of solid state analog diodes	Equation A Upper Limit C=3219 Lower Limit C=2
No. of Cathode Ray Tubes (R)	The number of CRTs in the system.	R	Equations A and B Upper Limit=11 Lower Limit=0

(Extracted from RADC-TDR-63-300, Supplement 1)

Table IX-10. Continued

Parameter	Definition	Quantification of Parameter	Range of Validity
Frequency (F)	The highest frequency characteristic of the system, in megacycles per second. (In many cases, the highest frequency characteristically found in a system must be estimated on the basis of engineering judgement, as in the case of a radar repeater. The influence of this parameter on the result is such that an error in the estimate of frequency of a factor of two or three will be acceptable.) In the case of tunable equipment, the upper limit of the tuning range will be the estimated highest characteristic frequency; e.g., in the case of a 225-Mc/400 Mc radio set, the frequency to be used is 400 Mc. The units of frequency in the equation are megacycles.	Ln F	Equation C Upper Limit F=2900 MC Lower Limit F=0.001 MC
Maximum D.C. Voltage (V)	The maximum sready-state D.C. voltage in the system in kilovolts. Pulse and transient voltages are specifically excluded.	Ln V	Equation B Upper Limit 23.0 KV Lower Limit 0.73 KV Equation C Upper Limit 15.0 KV Lower Limit 0.015 KV

(Extracted from RADC-TDR-63-300, Supplement 1)

Table IX -10. Continued

Parameter	Definition	Quantification of Parameter	Ranges of Validity
Power Consumption (P)	Power consumption is the rated operating power consumption requirement in kilowatts including the power consumption during a "radiate" or "transmit" condition. It specifically excludes momentary power surges required for motordriven tuning and other transient operations.	Ln P	Equation A Upper Limit 399.5 KW Lower Limit 0.033 KW Equation B Upper Limit 399.5 KW Lower Limit 0.182 KW

(Extracted from RADC-TDR-63-300, Supplement 1)

Independent Variables X_i	Mean of Independent Variables $\overline{X}_i$	Deviation $(X_i - \overline{X}_i)$
X_a =	5.274	
X_b =	1.560	
X_c =	1.911	

(a) Factor 1	(b) Factor 2	(c) Multiplier	(d) Product (a) (b) (c)
$(X_a - \overline{X}_a)$ =	$(X_a - \overline{X}_a)$ =	0.032	
$(X_b - \overline{X}_b)$ =	$(X_b - \overline{X}_b)$ =	0.080	
$(X_c - \overline{X}_c)$ =	$(X_c - \overline{X}_c)$ =	0.004	
$(X_a - \overline{X}_a)$ =	$(X_b - \overline{X}_b)$ =	-0.022	
$(X_a - \overline{X}_a)$ =	$(X_c - \overline{X}_c)$ =	-0.006	
$(X_b - \overline{X}_b)$ =	$(X_c - \overline{X}_c)$ =	0.021	
		SUBTOTAL	
		ADD Constant Value	1.020
		f=TOTAL	
		s =	0.400
		$K = 2\,(\sqrt{f}\,)\,(s)$ =	
		$g = e^K$ =	

(Extracted From RADC-TDR-63-300 Supplement 1)

Figure 9-12 Worksheet for Computing Confidence Interval for Equation A

Independent Variables X_i	Mean of Independent Variables $\bar{X}_i$	Deviation $(X_i - \bar{X}_i)$
X_b =	2.325	
X_d =	1.416	
X_c =	3.278	

(a) Factor 1	(b) Factor 2	(c) Multiplier	(d) Product (a) (b) (c)
$(X_b - \bar{X}_b)$ =	$(X_b - \bar{X}_b)$ =	0.015	
$(X_d - \bar{X}_d)$ =	$(X_d - \bar{X}_d)$ =	0.059	
$(X_c - \bar{X}_c)$ =	$(X_c - \bar{X}_c)$ =	0.191	
$(X_b - \bar{X}_b)$ =	$(X_d - \bar{X}_d)$ =	0.011	
$(X_b - \bar{X}_b)$ =	$(X_c - \bar{X}_c)$ =	0.045	
$(X_d - \bar{X}_d)$ =	$(X_c - \bar{X}_c)$ =	-0.058	
		SUBTOTAL	
		ADD Constant Value	1.043
		f= TOTAL	
		$\sqrt{f}$	
		s =	0.427
		$K = 2(\sqrt{f})(s)$ =	
		$g = e^K$ =	

(Extracted from RADC-TDR-63-300 Supplement 1)

Figure 9-13 Worksheet for Computing Confidence Interval for Equation B

Independent Variables X_i	Mean of Independent Variables $\overline{X}_i$	Deviation $(X_i - \overline{X}_i)$
X_d =	0.247	
X_e =	2.733	

(a) Factor 1	(b) Factor 2	(c) Multiplier	(d) Product (a) (b) (c)
$(X_d - \overline{X}_d)$ =	$(X_d - \overline{X}_d)$ =	0.057	
$(X_e - \overline{X}_e)$ =	$(X_e - \overline{X}_e)$ =	0.010	
$(X_d - \overline{X}_d)$ =	$(X_e - \overline{X}_e)$ =	0.032	
		SUBTOTAL	
		ADD Constant Value	1.037
		f=TOTAL	
		$\sqrt{f}$ =	
		s =	0.460
		$K = 2(\sqrt{f})(s)$ =	
		$g = e^K$ =	

(Extracted from RADC-TDR-63-300 Supplement 1)

Figure 9-14 Worksheet for Computing Confidence Interval for Equation C

as well as the overall function of the equipment. The LRU level prediction will not be described here, however, because to do so would require excessive space.[2]

The technique for predicting airborne equipment reliability includes the following steps:

a. The general type of equation to be used is determined based on the general type of information available. Two types of equations are defined for reliability prediction at the equipment level. These are:

   Type I - General mission/performance parameters are known, as during the Definition Phase of system development.

   Type II - Detailed performance/design parameters are defined, as during the early Acquisition Phase.

b. The appropriate equipment classification is determined based on the definitions in Table IX-11. This table also includes a description of the sample that was used in developing the technique. These descriptions can be used in determining the extent to which the equipment under consideration compares with the sample equipments.

c. The appropriate prediction equation and the ranges of prediction parameters are selected using Table IX-12. The equations for the "all equipments" class should be used with caution and only if one or more of the parameter ranges of the appropriate class are exceeded.

d. The prediction parameters applicable to the selected prediction equation are identified and quantified using Table IX-13.

e. The confidence interval for the reliability prediction is determined using the following equations:

$$\ell n\, \theta_L = \ell n\, \hat{\theta} - k;\ \theta_L = (e^{-k})\hat{\theta}$$

$$\ell n\, \theta_U = \ell n\, \hat{\theta} + k;\ \theta_U = (e^{k})\hat{\theta}$$

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[2] For a detailed description of the technique for considering the LRU in predicting reliability by function, the reader is referred to the references cited in paragraph 6c.

Table IX-11 Equipment Classifications

Classification	Definition	Description of Sample
Navigational and Radio Receiving Sets	Determines navigational parameters by the receiving and processing of signals from external sources or by the receiving and detecting of various signals used in connection with air traffic control and landing aids.	The sample represents 15 equipments with a range in MTBF of from 13 to 2975 hours. All receivers are shock mounted; only one contains printed circuits; no redundancy is incorporated, and both tubed and transistorized sets are well represented. The receivers consist of marker beacon, direction finder, Loran, glide slope, data link, localizer, and Sonobouy receivers.
Electromechanical Analog Navigational Computers	Accepts electrical input signals from a variety of aircraft sources such as static pilot tubes, doppler information, gyroscopes, and compass systems. The computer integrates these inputs into useful navigational information for display to the aircraft's crew. These computers contain no electromagnetic transmitting or receiving functions.	The sample is characterized by these computers's use of servo systems to solve simple trigonometric relations. This group consists of 14 computers, including Air Data Computers, True Airspeed, Inertial Navigational, and Target Positioning Computers. MTBF ranges from 14 to 413 hours. All but 2 of the computers were transistorized and all were analog in operation.
Indicator Groups	Displays processed information from a variety of on-board equipments; consists of self-contained devices, but this class does not include those indicators classified as pilot's instruments and used as flying aids.	The sample is derived from 5 equipments with MTBF's ranging from 60 to 162 hours. Coordinate data sets and PPI displays are represented. The high observed correlation is partially a result of the small sample size.
Signal Processing/Generating Equipment	Performs the intermediate function of generating or processing signals for display or for use in other equipments. The class consists of coder/decoders, signal analyzers, and signal converters.	The sample represents only 4 equipments, three of which perform distinctly different functions; yet all are within the classification of signal processing or generating. The equipments are the Signal-Data Converter, Signal Analyzer, and Coder-Decoder. The MTBF for these equipments ranges from 28 to 413 hours. The high observed correlation is partially because of the small sample size.
Radio Command Communications	Provides air-ground or air-air radio communications receiving and transmitting sets.	The sample represents 12 equipments of the AN/ARC series. The equipments use CW, AM, FM, and SSB emission in frequency ranges of from 9 to 400 mc. All sets that use SSB modulation have a power output of 100 watts or more, whereas the sets using CW, AM, FM, have power outputs ranging from 2 to 50 watts. The MTBF of these equipments ranged from 8 to 521 hours. Only one transistorized equipment is in this group; the remaining sets use standard, miniature, and subminiature tubes; 75% of the sets provide fully automatic tuning. Only one set is manually tuned.
High-Power Radar Sets	Provides high effective peak output power (5 KW or greater).	The sample represents 15 radar sets which have an MTBF range of from 5 to 50 hours. Most of the parameters observed have well distributed values throughout their respective ranges for all fifteen radar sets analyzed. Care should be used in determining the values of the significant variables for this class. Particular caution should be taken in the determination of operational functions other than those listed as representative of this parameter.
Low-Power Navigational and IFF Transmitting and Receiving Sets	Provides relatively low-power outputs (less than 5 KW effective peak power), and all equipments in this class perform both a receiving and transmitting function. This class includes doppler, beacons, TACAN, altimeters, and IFF.	This sample represents 22 sets, the largest group. It also represents the widest variety of equipment types, including doppler, beacons, TACAN, altimeters, and IFF. The MTBF for this group ranges from 14 to 459 hours. One altimeter utilized an analog system at low altitudes and pulsed system at high altitudes. Frequencies range from about 1 to 30 KMHz.
Intercommunication Sets	Provides communications between on-board aircraft stations; also works in conjunction with on-board radio receiving and transmitting sets.	This sample represents 6 equipments, with a range in MTBF of from 40 to 800 hours. Two of the six equipments studied use vacuum tubes; the remaining four equipments are transistorized. The equipments can accommodate from 4 to 17 channels. Some of the sets provide their own power, the others use the aircraft's power directly. The high observed correlation is partially because of the small sample size.

(Extracted from RADC-TR-66-509)

Table IX-12 Avionics Equipment Reliability Prediction Equations

Equipment Classification	Equation Type	Equation	Parameter Range
Navigational and Radio Receiving Sets	I	$\ln\hat{\theta} = 5.796 - 0.561(X_1) - 0.336(X_2) + 0.232(\ln X_3)$	$0.1 \le X_1 \le 4.5$ $0 \le X_2 \le 4$ $2 \le X_3 \le 500$
	II	$\ln\hat{\theta} = 3.529 - 0.612(X_1) - 0.345(X_2) + 0.150(X_4)$	$0.1 \le X_1 \le 4.5$ $0 \le X_2 \le 4$ $15 \le X_4 \le 22$
Electromechanical Analog Navigational Computers	I & II	$\ln\hat{\theta} = 1.806 - 0.120(X_5) + 0.298(X_6)$	$3 \le X_5 \le 20$ $9 \le X_6 \le 13$
Indicators	II	$\ln\hat{\theta} = 5.515 - 0.163(X_7)$	$2 \le X_7 \le 8$
Signal Processing/Generating Equipment	I & II	$\ln\hat{\theta} = 6.283 - 0.0176(X_{13})$	$20 \le X_{13} \le 168$
Radio Command Communications	I & II	$\ln\hat{\theta} = 8.779 - 0.708(\ln X_{14}) - 0.354(\ln X_{15})$	$9 \le X_{14} \le 400$ $2 \le X_{15} \le 400$
High Power Radar Sets	I	$\ln\hat{\theta} = 3.317 - 0.267(X_{16}) - 0.136(X_{17}) + 0.291(X_{18})$	$1 \le X_{16} \le 4$ $2 \le X_{17} \le 9$ $2 \le X_{18} \le 4$
	II	$\ln\hat{\theta} = 4.164 - 0.325(X_{16}) - 0.270(\ln X_7)$	$1 \le X_{16} \le 4$ $5 \le X_7 \le 185$
Low Power Navigation & IFF Transmitting & Receiving Sets	I & II	$\ln\hat{\theta} = 4.349 - 0.445(X_2) + 0.350(X_8)$	$0 \le X_2 \le 5$ $0 \le X_8 \le 3$
Intercommunication Sets	I	$\ln\hat{\theta} = 6.973 - 1.215(X_1) - 1.155(X_9)$	$0.1 \le X_1 \le 2.0$ $4 \le X_9 \le 17$
	II	$\ln\hat{\theta} = 7.108 - 0.0202(X_{10}) - 0.507(X_1)$	$20 \le X_{10} \le 140$ $0.1 \le X_1 \le 2.0$
All Equipments	I	$\ln\hat{\theta} = 2.986 + 0.242(X_{11}) - 0.226(\ln X_1)$ $-0.112(X_2) + 0.0949(X_6)$	$1 \le X_{11} \le 10$ $0.1 \le X_1 \le 48.7$ $0 \le X_2 \le 11$ $5 \le X_6 \le 13$
	II	$\ln\hat{\theta} = 4.707 - 0.141(\ln X_{10}) + 0.183(X_{11})$ $-0.443(\ln X_{12}) + 0.0625(X_4)$	$14 \le X_{10} \le 11{,}000$ $1 \le X_{11} \le 10$ $4 \le X_{12} \le 579$ $8 \le X_4 \le 22$

(Extracted from RADC-TR-66-509)

Table IX-13 Avionic Equipment Parameters and Quantification

Parameter Symbols	Parameter	Quantification
X_1	Volume	Equipment volume in cubic feet Note: For Radio and Navigational Receiving Sets, the volume of any antenna which may be a part of the set is not included in the calculation.
X_2	Number of Interfacing Equipments	The number of other equipments, excluding indicators, that feed signals to or receive signals from this equipment.
X_3	Sensitivity	Measured in μ volts for a 10 db $\frac{S+N}{N}$
X_4	Packaging Characteristic Rating Characteristic: — Rating Type of Enclosure Some cabinets pressurized — 0 No cabinets pressurized — 4 Vibration Isolation Some cabinets shock mounted — 4 No cabinets shock mounted — 0 Equipment Packaging Equipment in single package — 4 Equipment in 2 to 4 packages — 3 Equipment in 5 to 8 packages — 2 Equipment in 9 or more packages — 1 Type of Cooling Forced air-refrigerated (at all times) — 4 Forced air-inside ambient (at all times) — 3 Convection — 2 Refrigerated air on deck, outside ambient at altitude — 1 Component Packaging Modularized — 0 Conventional Construction — 4 Type of Wiring Printed Circuits — 0 Conventional Wiring — 4	The sum of the ratings given to each characteristic for the equipment under study.
X_5	Number of Signal Inputs Acceptable	The number of signals from other equipments which the equipment under study requires or can accomodate in its operation.
X_6	Equipment Feature Rating Feature: — Rating Power Supply Power supply external to equipment — 5 Solid State — 4 Combination solid state and tubes — 3 Tube — 2 Rotating machinery — 1 Tuning (Operational) None required — 4 Manual — 3 Semi-automatic (auto-tune) — 2 Fully automatic — 1 Type of Indicators None — 4 Meters — 3 Electro-mechanical — 2 Cathode ray tube — 1	The sum of ratings for the applicable individual design features.
X_7	Number of LRU's LRU Function (MIL-STD-196A Symbol): Air conditioning (HD); Amplifier (AM); Antenna, complex (AS); Antenna, simple (AT); Compensator (CN); Computer (CP); Control (C); Converter (CV); Coupler (CU); Indicator, Cathode Ray Tube (IP); Indicator, Non C.R.T. (ID); Junction Box (J); Keyer (KY); Power Supply (PP); Receiver (R); Receiver/Transmitter (RT); Recorder (RD); Relay Box (RE); Switch (SA); Transmitter (T)	The sum of the total quantity of each LRU included in the equipment complement.
X_8	Equipment Subfunction rating for Low Power Navigation and IFF Transmitting and Receiving Sets. Subfunction: — Rating Doppler, TACAN, Radio Altimeters — 1 Beacons — 2 IFF Sets — 3	The rating of the subfunction.

(continued)

Table IX-13 (Continued)

Parameter Symbols	Parameter	Quantification
X_9	Number of Channels	The number of channels of operation for intercommunication sets.
X_{10}	Power Consumption	The steady state power in watts consumed by the equipment in its most power-consuming mode of operation. Note: Considers the "radiate" not the "standby" status of radar sets. "Steady state" implies that starting power requirements are not to be considered.
X_{11}	Equipment Function Rating Classification Function: — Rating Navigational Receiving Sets Loran — 6 Radio Receiving Sets — 3 Radio Navigation Sets — 5 Direction Finder Equipment — 5 Electromechanical Analog Navigation Computers Navigation Computers — 1 Indicator Group Indicators — 3 Signal Processing/Generating Equipment Signal Converter — 2 Signal Analyzers — 2 Coder-Decoder — 10 Radio Command Communications Radio Command Communications — 2 High-Power Radar Sets Intercept — 1 Tracking — 1 Side-Looking — 1 Search — 1 Fire Control — 1 Bombing/Navigation — 1 Acquisition — 1 Low Power Navigational and IFF Transmitting and Receiving Sets IFF — 5 Doppler — 2 Beacons — 3 TACAN — 2 Altimeters — 2 Intercommunications Intercom Sets — 4	The rating given to the equipment function.
X_{12}	LRU Rating LRU Function (MIL-STD-196A Symbol):* HD 2; AM 3; AS 4; AT 1; CN 2; CP 4; C 3; CV 3; CU 1; IP 4 ID 2; J 3; KY 4; PP 4; R 4; RT 4; RO 4; RE 4; SA 2	The sum of the products of the quantity of each of the LRU types shown below times the rating for that LRU type.
X_{13}	Weight	The weight in pounds of the equipment. Note: For Radio Navigational and Receiving Sets, the weight of any antenna that may be a part of the set, is excluded from the calculation.
X_{14}	Frequency	The highest frequency of operation in megacycles per second.
X_{15}	Power Output	The power in watts delivered to the antenna.
X_{16}	Number of Operational Functions or Capabilities Radar Set Functions: Airborne Early Warning and Control; Anti-Intrusion; Acquire on Jammer; Acquisition; Bombing; Calibrating (Test Equipment); CW Illumination; ECM Training; Ground Controlled Approach; Gun Fire Control; Home on Jammer; Height Finding Radar; IFF/SIF Intercept; Navigation; Noise Jamming; Projectile Intercept; Radar Decoy; Radar Beacon; Radar Trainer; Ranging; Reconnaissance; Search; Track; Any functions not otherwise listed of the same order	The total number of the functions contained by the radar set:

* See X_7 for definitions of symbols.

(continued)

Table IX-33 (Continued)

Parameter Symbols	Parameter	Quantification
X_{17}	Number of Features **Features:** MTI Multiple Ranges ECCM Self contained computer Self contained display Variable pulse width Beam shaping (i.e., cosecant squared) Variable Scan characteristics Variable range bug Self contained gyro Contains beacon receiver	The sum of the number of the features contained by the radar set.
X_{18}	Type of Active Element Group (AEG) Type of AEG (Predominant) — Rating Transistor — 4 Tube, Standard or miniature — 3 Tube, subminiature — 2 Electromechanical devices — 1	The rating for the type of AEG used. Use average of ratings if more than one type dominates.

(Extracted from RADC-TR-66-509)

where

θ_L and θ_U are the lower and upper confidence limits, respectively, and

$$k = t_{(\alpha/2, d)}\, s \left(\frac{1}{m} + \sum c_{ii} x_i^2 + 2 \sum_{j=i+1}^{r} \sum_{i=1}^{r-1} c_{ij} x_i x_j \right)^{1/2}$$

where

m = number of observations used in the regression analysis

r = number of independent variables

$t_{(\alpha/2, d)}$ = t statistic for a 100 $(1 - \alpha)$% two-sided confidence interval based on $d = (m-r-1)$ degrees of freedom

s = standard error of estimate

c_{ij} = Gauss multiplier

x_i = Deviation $(X_i - \overline{X}_i)$ where X_i is the value of the i^{th} independent variable to be used for the prediction and $\overline{X}_i$ is the mean value of the i^{th} independent variable of the equipments used in the regression analysis.

If one-sided limits are desired, the t statistic $t_{(\alpha, d)}$ is used to compute k; for a one-sided lower limit, subtract k from $\ln \theta$; for a one-sided upper limit, add k. Table IX-14 presents the information required to compute k. The t statistic shown in the table is for a two-sided 90% confidence interval or a one-sided 95% confidence interval. Also shown in Table IX-14 is the sample multiple correlation coefficient, R, for each equation.

7. PART COUNT PREDICTION TECHNIQUES

Reliability prediction techniques are available for application when data such as estimated part inventories are available, but when the design details necessary for applying the more detailed stress analysis techniques are not known. These techniques make use of "average" failure rates for general classes and types of parts, based on data acquired from field experience on a large variety of equipment. The

Table IX-14 Factors for Determining Confidence Intervals for Prediction Equations

Equation Number	Equipment Classification	R	t (for 90% C.L.)	s	m	Variable i - Code	$\overline{X}_i$	Gauss Multipliers
1 (Early)	Radio and Navigational Receiving Sets	0.800	1.796	0.792	15	1 X_1	1.345	c_{11}= 0.0510
								c_{12}= 0.00783
						2 X_2	1.652	c_{22}= 0.0359
								c_{13}= 0.0210
								c_{23}= 0.000795
						3 $\ln X_3$	1.763	c_{33}= 0.0550
2 (Late)	Radio and Navigational Receiving Sets	0.804	1.796	0.785	15	1 X_1	1.345	c_{11}= 0.0442
								c_{12}= 0.00733
						2 X_2	1.652	c_{22}= 0.0359
						3 X_4	18.427	c_{13}= 0.00506
								c_{23}=-0.000792
								c_{33}= 0.0202
3 (Early and Late)	Electromechanical Analog Navigational Computers	0.824	1.796	0.601	14	1 X_5	10.147	c_{11}= 0.00172
						2 X_6	10.480	c_{12}=-0.00426
								c_{22}= 0.127
4 (Late)	Indicator Groups	0.938	2.353	0.166	5	1 X_7	5.398	c_{11}= 0.0442
5 (Early and Late)	Signal Processing/Generating Equipment	0.962	2.920	0.453	4	1 X_{13}	72.2	c_{11}= 0.0000603
6 (Early and Late)	Radio Command Communications	0.719	1.833	0.761	12	1 $\ln X_{14}$	5.177	c_{11}= 0.0937
						2 $\ln X_{15}$	3.420	c_{12}= 0.0596
								c_{22}= 0.0798
7 (Early)	High Power Radar Sets	0.753	1.796	0.401	15	1 X_{16}	2.632	c_{11}= 0.118
								c_{12}=-0.0221
						2 X_{17}	6.161	c_{22}= 0.0274
						3 X_{18}	2.626	c_{13}= 0.0582
								c_{23}=-0.0378
								c_{33}= 0.0252
8 (Late)	High Power Radar Sets	0.766	1.782	0.375	15	1 X_{16}	2.632	c_{11}= 0.102
						2 $\ln X_7$	2.841	c_{12}=-0.0221
								c_{22}= 0.0899

Table IX-14 Continued

Equation Number	Equipment Classification	R	t (for 90% C.L.)	s	m	Variable i - Code	$\bar{X}_i$	Gauss Multipliers
9 (Early and Late)	Low Power Navigation and IFF Transmitting and Receiving Sets	0.750	1.729	0.610	22	1 X_2 2 X_8	1.720 1.418	c_{11}= 0.0418 c_{12}= 0.0206 c_{22}= 0.0845
10	Intercommunication Sets	0.871	2.353	0.517	6	1 X_1 2 X_9	0.546 12.710	c_{11}= 0.611 c_{12}= 0.0419 c_{22}= 0.0122
11 (Late)	Intercommunication Sets	0.922	2.353	0.407	6	1 X_{10} 2 X_1	98.708 0.546	c_{11}= 0.000290 c_{12}=-0.00448 c_{22}= 0.536
12	All Equipments	0.657	1.645	0.921	94	1 X_{11} 2 $\ln X_1$ 3 X_2 4 X_6	1.892 0.850 2.888 8.653	c_{11}= 0.00413 c_{12}= 0.000887 c_{13}= 0.000318 c_{14}=-0.00132 c_{22}= 0.00802 c_{23}=-0.00156 c_{24}= 0.00197 c_{33}= 0.00240 c_{34}=-0.00103 c_{44}= 0.00394
13 (Late)	All Equipments	0.735	1.645	0.828	94	1 $\ln X_{10}$ 2 X_{11} 3 X_{12} 4 X_4	6.482 1.892 3.004 15.019	c_{11}= 0.0173 c_{12}= 0.00429 c_{13}=-0.0133 c_{14}= 0.000996 c_{22}= 0.00512 c_{23}=-0.00231 c_{24}=-0.000535 c_{33}= 0.0234 c_{34}= 0.000228 c_{44}= 0.00120

(Extracted from RADC-TR-66-509.)

technique described below is typical of currently used part count prediction techniques.

This technique permits estimating equipment failure rate based on part count (actual or estimated) by class or type. The technique involves counting the number of parts of each class or type, multiplying this number by the generic failure rate for each part class or type, and summing these products to obtain the failure rate for the equipment. The procedure distinguishes a part class as being all parts of a given function (e.g., resistors, capacitors, transformers). Part types are used to further define parts within a class (e.g., fixed composition resistors, fixed wire wound resistors).

Table IX-15 provides average failure rate values for a variety of parts, by class and type. These values were derived from Volume II of this notebook by assuming a fixed ground environment, operation at 50°C, and 50% stress ratio. The values have been calculated for "lower-grade" parts, i.e., standard military parts bought to lesser MIL-specification and without requiring any special reliability controls (see page 3 of Volume II). Other modifying factors, such as resistance factor, construction class factor, etc., were assumed as appropriate based on engineering judgment.

The part count prediction is performed as follows:

a. All parts in the equipment under consideration are classified according to the classes and types listed in Table IX-15.

b. The total number of parts in each class and type is determined by actual count if possible. If an actual count is not possible, the best estimate of part count is obtained.

c. The average failure rate is obtained from Table IX-15 for each type of part used in the equipment.

d. The equipment failure rate is determined using the expression

$$\lambda_E = \sum_{i=1}^{n} N_i \lambda_i$$

where:

λ_E = The equipment failure rate

N_i = The number of parts of type i included in the equipment

TABLE IX-15. Average Part Type Failure Rates

Part Class and Type		Failure Rate* (% per 1,000 hours)
CAPACITORS		
MIL-C-25,	Paper Foil	.001
MIL-C-14157,	Paper, Paper Mylar	.001
MIL-C-18312,	Mylar-Metallized	.001
MIL-C-19978,	Mylar or Teflon	.036
MIL-C-19978,	Polystyrene	.041
MIL-C-27287,	Plastic Film	.0038
MIL-C-3965,	Tantalum Foil	.045
MIL-C-3965,	Tantalum, Wet Slug	.032
MIL-C-26655,	Solid Tantalum	.0024
MIL-C-39003,	Solid Tantalum	.0024
MIL-C-62,	Aluminum, Wet Foil	.142
MIL-C-5,	Mica, Molded	.0018
MIL-C-5,	Mica, Dipped	.00086
MIL-C-5,	Mica, Button	.063
MIL-C-11272,	Glass & Porcelain Enamel	.0032
MIL-C-20,	Ceramic, Low K	.0322
MIL-C-11015,	Ceramic, High K	.018
MIL-C-81,	Variable, Ceramic	.568
MIL-C-14409,	Variable, Glass Piston	.039

Table IX-15 (cont'd)

Part Class and Type		Failure Rate* (% per 1,000 hours)
RESISTORS		
MIL-R-11,	Carbon Composition	.00207
MIL-R-11804,	Power Film	.160
MIL-R-10509,	Precision Film	.0015
MIL-R-55182,	Fixed Established Rel. Film (Rel. Level R)	.00006
MIL-R-22684,	Insulated Fixed Film	.0186
MIL-R-93,	Accurate Wirewound Fixed	.0397
MIL-R-26,	Power Wirewound Resistors	.0390
MIL-R-12934,	Precision Wirewound Potentiometer	.500
MIL-R-19,	Semi-precision Wirewound Pot.	.235
MIL-R-94,	Low Precision Composition Pot.	.700
MIL-R-22097,	Non-Wirewound Trimmer Pot.	.630
MIL-R-27208,	Wirewound Trimmer Pot.	.099
MIL-R-39015,	Established Rel. Wirewound Pot. (Rel. Level R)	.0126
MIL-R-22,	High Power Wirewound Pot.	.168
CONNECTORS,	Grade C (per mated pair)	.0324
RELAYS,	General Purpose DPDT	.072
SWITCHES,	Snap-action DPDT	.450
MOTORS,	Case B, grade 1, split-phase	.0153

Table IX-15 (cont'd)

Part Class and Type	Failure Rate* (% per 1,000 hours)
FANS & BLOWERS	6.3
SYNCHROS & RESOLVERS	.080
AUDIO TRANSFORMERS	.0038
MAGNETIC AMPLIFIERS (<100v)	.0075
POWER TRANSFORMERS & FILTERS, Low-level	.00625
MICRO-SIZED MAGNETIC DEVICES, All Types	.075
RF TRANSFORMERS & COILS	.0938
LOW-LEVEL PULSE TRANSFORMERS	.0019
DIODES	
Logic Switching	.023
Power Rectifier	.110
TRANSISTORS	
Analog, Silicon, npn	.128
Digital, Silicon, npn	.039
MICROCIRCUITS	
Digital, Average Grade	.0840
Linear, Average Grade	.2520
TUBES	
Receiving Tubes, See Table X-3, page 295 of Volume II Transmitting Tubes, See Table X-7, page 303 of Volume II Special Purpose Tubes, See Table X-8, page 306 of Volume II	

*NOTE: These failure rates were derived from Volume II of the RADC Reliability Notebook, assuming a fixed ground environment, operation at 50° C and a 50% stress ratio, and are for "lower grade" parts.

λ_i = The average failure rate of parts of type i

n = The number of different types of parts included in the equipment

8. STRESS ANALYSIS PREDICTION TECHNIQUES

Several reliability prediction techniques have been developed that permit a detailed part-by-part analysis of a system design to the extent that the effects of degrading stresses are considered in determining the failure rates of individual parts. These techniques are all similar in application, the major difference being the source of failure rate data, and the corresponding differences in the procedures used in extracting data from the data source, and translating these data for application to a specific system. Once the failure rate data are obtained, the reliability prediction is completed by combining the failure rates for each part in the system according to a pre-established mathematical model. In general, this will involve substituting failure rates for the λ_i values in expressions such as equations (10) and (11) of paragraph 2.3 of this chapter to obtain the predicted reliability or MTBF of an element of the system, and combining system element reliabilities as appropriate to obtain a prediction of the overall system reliability.

Volume II of this notebook is a recommended source of failure rate data suitable for application in performing stress analysis prediction techniques. Failure rate data and related information are organized by part class (i.e., resistors, potentiometers, etc.) and type or style (e.g., composition resistor, film resistors and wirewound resistors).

The procedure for extracting failure rate data from Volume II differs according to part class and type. In general, however, the following steps are required:

a. Operational and environmental stresses and other characteristics are determined for each part in the subject equipment or system. The specific types of parameters and characteristics that must be defined and evaluated varies with part class. The extent of this step of the procedure is indicated by Figure 9-15, which lists the general types of parameters and characteristics that must be considered in determining failure rates for parts in each class.

b. A base failure rate is determined for each part. This value is established from the appropriate chart in Volume II, and is a function of part type, environmental temperature, and the relative level of the more significant operational stress.

PARAMETER OR CHARACTERISTIC	PART CLASSIFICATION											
	RESISTORS	POTENTIOMETERS	CAPACITORS	CONNECTORS	RELAYS	SWITCHES	MAGNETIC DEVICES	ROTATING DEVICES	ELECTRON TUBES	SEMICONDUCTOR DEVICES	MICROELECTRONIC DEVICES	WIRE AND CABLE
Applicable Specification	✓	✓	✓	✓			✓					✓
Service or Application	✓	✓	✓		✓		✓	✓		✓	✓	
Type, Style, Grade, etc.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reliability Grade	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Temperature, Rated					✓		✓	✓		✓		✓
Temperature, Operating	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Power, Rated	✓	✓							✓	✓		
Power, Operating	✓	✓							✓	✓		
Voltage, Rated			✓						✓	✓		
Voltage, Operating	✓	✓	✓						✓	✓		
Current, Rated									✓	✓		✓
Current, Operating									✓	✓		✓
Load, Rated					✓			✓				
Load, Operating		✓						✓				
Load, Type (Res, Ind, etc.)					✓							
Environment	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Operating Time/Life Req.	✓	✓						✓				
Duty Cycle									✓			
Cycling (on-off) Rate		✓			✓	✓						
Speed (RPM, etc.)								✓				
Resistance	✓	✓					✓					
Initial Tolerance	✓											
Number of Brushes								✓				
Number & Form of Contacts		✓		✓	✓	✓	✓					✓
Number of Sections/Decks		✓				✓						
Number of Input/Outputs											✓	
Number of Windings								✓				
Pin Size				✓								
Insert Material Insulation				✓			✓	✓				✓
Case/Frame Size			✓					✓				
Weight							✓					

Figure 9-15 Parameters and Characteristics Considered in Failure Rate Prediction

c. The values of one or more multiplicative or additive factors are determined from tables or charts in Volume II. These factors define the relationship between the base failure rate and the predicted failure rate for the specific application of interest.

d. The part failure rate is calculated using the established base failure rate and the modifying factor. Equations for performing these calculations are provided in Volume II.

Stress analysis failure rate predictions such as this permit extremely detailed analyses of equipment or system reliability. However, since details of the system design are required in determining stress ratios, temperature and other application and environmental data, these techniques are only applicable during the late stages of design. Also because of the high level of complexity of modern systems, the application of the procedure is time consuming, and should only be used when such detailed part-by-part analysis is warranted. Computer processing of reliability data is normally feasible. However, the initial stress analysis usually involves considerable effort at the engineering level.

9. DEGRADATION ANALYSIS PREDICTION TECHNIQUES

Degradation analysis is a general term defining a variety of analysis techniques which permit an evaluation of the probable susceptibility of an equipment to variation or drift of circuit parameters. In general, degradation analysis is performed using any of a number of circuit design analysis techniques. These techniques are basically similar in that they involve a computer solution of a mathematical model describing circuit output variables in terms of the several interrelated input parameters. The results of a degradation analysis can provide information concerning the relationships between input and output parameter variation or drift, and can have valuable application in the solution of a variety of reliability design problems such as achieving maximum circuit stability within specified performance constraints, or identifying most likely causes of failure.

Many proven circuit analysis techniques suitable for degradation analysis are currently available for use. Some techniques are more applicable to circuit design while others are effective in predicting circuit performance under a range of conditions. The former type is generally useful in optimizing a circuit design in terms of reliability, while the latter type can be used to provide a measure of circuit reliability under a variety of operational environments, or after a given period of service. Some techniques can only be used on linear circuits while others may be used on nonlinear circuits as well. Some are intended for static analysis of d.c. or a.c. circuits while others

can be used for dynamic transient analyses. Also, input data requirements range from simple nominal and limiting values to complete statistical distributions of parameter values.

Because of the large number and complexity of analysis techniques available, a detailed discussion of degradation analysis is not within the scope of this notebook. However, many of the available techniques can be identified as being developed from, or similar to, one of the four general methods discussed below. These methods are categorized for the purposes of this discussion as the "parameter variation", "worst case", "moment", and "Monte Carlo" methods of circuit analysis. The following discussions are presented to aid in identifying a particular technique with reference to one of these general methods. In addition, significant characteristics of each method are summarized in Table IX-16 to aid in selecting an appropriate method for a given application.

9.1 Parameter Variation Methods

Parameter variation methods can provide information concerning part parameter drift stability, circuit performance-part parameter relationships, and certain circuit-generated stresses. These methods require the least amount of input information of the four methods discussed here, and do not require extensive data from large sample life tests on circuit elements. In general, input data consists of nominal or mean values and estimated or assumed circuit parameter drift characteristics.

In the general case, a parameter variation analysis would consist of solving circuit equations in an iterative manner until a solution is obtained for all probable combinations of input parameter values. This general solution, however, would usually involve an excessively large number of solutions, and would be impractical in most applications. In view of this, typical parameter variation analyses are performed by varying each parameter independently (one-at-a-time) or in pairs (two-at-a-time).

A typical parameter variation method would be performed by varying one or two parameters at a time in discrete steps with all other parameters held at the nominal value. Solution of the circuit equations for each step would provide the limiting values of the particular parameters under investigation. This procedure is repeated for all parameters or pairs of parameters in the circuit.

Output data from an analysis of this type could include:

a. Parameter limits outside of which a failure would occur.

b. Maximum stress levels within the circuit, such as maximum power dissipated by a resistor or transistor, breakdown voltages, maximum or minimum biasing voltages or current.

Table IX - 16 Characteristics of Typical Circuit Analysis Techniques

Method	Parameter Variation	Worst-Case	Moment	Monte Carlo
Type Analysis:	General; one-at-a-time and two-at-a-time parameter variation.	Steady state a.c. and/or d.c. Worst Case.	Statistical: Considers parameter mean and variance.	Statistical: Considers distribution of input parameters.
Output Information Received:	Failure points for one-and two-at-a-time parameter variation.	Worst case value of output variable compared with allowable value.	Mean and variance of the distribution of each output parameter.	Histogram for each output variable.
Applicable Circuits:	Any steady state a.c. or d.c. circuit.	Class A amplifies, power supplies, d.c. circuits, logic circuits (each state, no switching).	Any circuit for which a mathematical model can be derived.	Any circuit for which a mathematical model can be derived.
Input Data Requirements:	Nominal value of each input parameter and range to investigate each.	Nominal value and end-of-life or tolerance limits for parts.	Mean (or nominal) value and standard deviation or variance of each input parameter. Correlation coefficient when necessary.	Complete distribution of each input parameter.
Mathematical Model:	Circuits simultaneous equation, or matrix equation.	Circuits simultaneous equations, or matrix equations.	Circuits simultaneous equation, or matrix equation.	Any mathematical representation that include input parameters.
Typical Program Capabilities:	100 input parameters 60 output variables.	75 input parameters 40 output variables.	100 input parameters 60 output variables.	125 input parameters 40 output variables.
Typical Use of Output:	Aid in circuit design and redesign. Determine probable causes of failure.	Aid in circuit design and redesign. Determine probable causes of failure.	Aid in circuit design and redesign. Predict future output parameter value.	Predict circuit performance at any time in future.
Other Considerations:	Relatively elementary input data requirements.	Use piece-part input data. Therefore, is useful relatively late in design.	Relatively fast program. Moderate input data requirements.	Most accurate analyses. Require extensive input data.

c. Most critical circuit parameters with respect to causing circuit failure.

9.2 Worst-Case Methods

Worst-case methods of circuit analyses can be used to determine the worst-case conditions for any output variable of the circuit. Once the worst-case conditions have been determined for any output variable, the value of that output variable is calculated and compared with the rated or specified value. The worst-case methods are extensions of the parameter variation methods in that output variables are evaluated with reference to varying values of the input parameters. The major difference is that all parameters are simultaneously varied, with each parameter being varied in the direction that produces an increased (or decreased) output. When each parameter value has reached the limit of its range (tolerance or expected drift limit) the worst-case output value is determined.

The worst-case method is somewhat more complex than the parameter variation method in that the computer program first evaluates partial derivatives of the circuit equations to determine the direction each parameter should be varied in reaching the worst-case condition. The circuit equations are then solved as the parameter values are varied in the appropriate direction. As the parameters reach the limiting values, the value of the output variable is calculated and recorded. Upon conclusion of the analysis, the program summarizes the results by listing the input parameters, output variables, and appropriate statements pertaining to the subsequent use of the data.

9.3 Moment Methods

Moment methods of circuit analysis bear this name because they make use of the mean and the second moment (variance) of the frequency distribution of input parameters to calculate the mean and variance of the circuit output variables. Assuming that the parameter distributions are normal, these quantities would completely describe the distribution of the output variable. Although distributions are rarely exactly normal, the results of an analysis usually provide meaningful approximation of the circuit characteristics.

The moment method analysis begins with the preparation of a set of simultaneous equations describing the circuit. The mean values for the circuit output variables are calculated using the mean values for each circuit parameter. The computer then calculates the variance of each output variable by means of the propogation of

variance formula. This statistical formula relates the variance of output variables to the mean, variance and correlation coefficients of input parameters.

Data inputs required for performing a moment analysis include a complete schematic diagram of the circuit being studied, together with nominal values, tolerances, and characteristics of all component parts. In addition, tabulations of the mean, variance, and correlation coefficients of all pertinent part parameters are required.

The outputs obtained from this type of analysis include the mean and variance of all output variables. In addition, the outputs can include voltages at nodes of the network, branch currents, resistor and transistor power dissipations, and other special variables of particular interest to the reliability engineer.

9.4 Monte Carlo Methods

Monte Carlo methods of network analysis involve the computer simulation of an empirical approach whereby a number of copies of the network under study are constructed by sampling component parts at random from a representative populatic of these parts. The empirical approach would require the process to be repeated many times, and measurements made and tabulated for all variables of interest for each copy of the network. It is obvious that such an approach would be excessively expensive and time consuming.

A computer simulation of this technique removes many of the undesirable features of an empirical approach. Such a simulation, known as the Monte Carlo method, is related to other computerized circuit analysis methods in that it begins with a mathematical model consisting of a set of circuit equations. However, the input data and computer time requirements for a Monte Carlo analysis are more severe than for other methods. However, these undesirable features are offset by the more detailed output information as compared to the other methods.

Input data for a Monte Carlo analysis must include the complete frequency distribution of each input parameter. For example, if a resistance value is required, then a set of values, distributed in a manner that is representative of the actual resistance values, would be provided. Random selection of a value from this set would then simulate the random selection of a resistor in the empirical approach.

Selecting all input parameter values in this manner, and solving the circuit equations using the parameter values selected, will result in one set of output variable values. Subsequent repetition of this process will provide a number of such sets, the distribution of which will simulate the distributions that would have been observed using the empirical approach. These distributions typically are presented in the form of a set of histograms or equivalent tabular data describing the distributions associated with each output variable. Thus, a Monte Carlo analysis will provide the most meaningful data concerning the expected performance of the circuit under investigation.

CHAPTER 10

RELIABILITY MEASUREMENT

1. INTRODUCTION

The objective of reliability measurement is to obtain an empirical assessment of the degree to which an equipment or system meets the reliability design requirements. Information on failures which occur during a test period in which equipments or components are subject to specified stresses provides data which can be used to compute component failure distributions or equipment reliability characterstics at specified levels of confidence. In this manner, the buyer of components or equipment obtains a numerical indication of the risk taken in accepting a production lot of specific size on the basis of reliability data obtained from reliability tests performed over a relatively short duration.

Modern reliability measurement procedures permit verification of compliance with specific reliability requirements by means of specified testing procedures which can be imposed as a contractual requirement. Thus, reliability tests are practical tools which can be used to assure that appropriately reliable equipments are being procured.

The Air Force requires that testing procedures be used to demonstrate the reliability of specific equipments and systems prior to their acceptance into inventory. Systems are normally tested in three phases: the Category I Test, the Category II Test, and the Category III test.

During the Category I Tests specific subsystem and equipments (CEI's) are usually tested by the contractor to determine if they meet the reliability requirements specified in the Part I Detail Specifications. Equipments are evaluated in a controlled environment at the contractor's plant, and performance is monitored by means of an instrumented test setup. Equipments that do not meet reliability requirements must be redesigned. However, when the mean-time-between-failures are high and testing will take a long time, the reliability demonstration tests of CEI's is done during system test.

In Category II Testing the individual equipments are mated and the entire system is subjected to realistic operational procedures and environment. These tests are typically a joint contractor/Air Force responsibility, and can either be performed in a simulated environment at the system contractor's plant, or in an actual field environment. These tests verify the overall system reliability, and the compatibility of subsystems and total system operational effectiveness.

At this time the government either accepts or rejects the system and its subsystems.

Category III testing or operational testing is supported by the SPO, but is performed by Air Force using command personnel, who exercise the total system in its actual operational environment. Reliability data are gathered along with many other types of operational data. The Category III Tests provide indications as to the reliability performance of Air Force Systems in realistic operating environments - these tests may uncover weaknesses masked in the previous tests.

In addition to these equipment and system reliability tests, individual parts and components also are subject to reliability testing when they are produced in production quantities. In this case, a sample of items drawn from a production lot is tested and the test results are used to decide on accepting or rejecting the entire production run at some specified level of confidence.

The techniques of mathematical statistics are used extensively in reliability test and demonstration. These techniques provide the tools to relate sample size, test duration, confidence levels, stress levels and other factors related to reliability demonstration.

Some of the basic statistical concepts used in reliability measurement, are summarized below, followed by a brief elementary discussion of Bayesian statistics as applicable to reliability evaluation. Also, relationships between certain statistical parameters that must be considered in reliability testing plans for equipments or systems, are presented together with procedures to aid in the utilization of MIL-STD-781B in the design of reliability test plans. The chapter is concluded with a brief discussion of certain considerations in the application of MIL-STD-105D in designing part reliability test plans.

2. STATISTICAL DISTRIBUTION OF RELIABILITY DATA

Reliability engineers make use of probability distributions to describe from the data the time to failure characteristics of components and equipments and use these statistical models to predict system reliability. Failure data are also utilized in conjunction with reliability test and demonstration procedures. Evaluation of such procedures is made by fitting the failure data to an assumed underlying distribution and determining whether the test criteria are satisfied. Therefore, a basic understanding of the use of statistical time to failure distributions is fundamental to the development of any reliability measurement program. In view of this, some typical distributions which appear frequently in the reliability literature, including the important exponential, Weibull, and gamma distributions are reviewed below.

2.1 Time To Failure Density and Distribution Functions.

A central concept in reliability theory is that of a failure density function or failure distribution function. These are analogous to the probability density function and probability distribution function encountered in probability theory. The density function measures the probability that a variable having a specific value will occur. The distribution function measures the probability that a chance occurrence will fall within a given range of values.

The density function can be illustrated by considering a discrete random variable, where the variable can assume only a given number of discrete values. The k possible values of the variable can be denoted by x_1, x_2, x_3......x_k. For a specific value of x, for example, x_2, the probability that a random trial will yield the value x_2 is represented by $f(x_2)$. This is the value of the "density function," $f(x)$ at $x = x_2$, and represents the relative number of times the value x_2 occurs out of all x's in the population. Pictorially, a density function for a discrete variable can be represented by a histogram such as that shown in Figure 10-1. The height of the bars represents the relative number of times each value of x occurs. The value $f(x_2)$ is represented by the height of x_2 bar.

The density function of a continuous variable, i.e., a variable that can take on any value, can be represented by the familiar "bell" curve such as that shown in Figure 10-2. The height of the curve at a given point on the x axis represents the value of the density function for that value of the variable. This curve will take on a variety of shapes, depending on the characteristics of the particular density function under consideration.

The distribution function, i.e., the function describing the probability that a variable value falls within a given range of values, effectively measures the total number of times values of the variable within a given range occur in relation to the total number of all possible values of the variable. In the discrete case, the distribution function is defined as the sum of all f(x) values for values of x falling within the range of interest. Mathematically, the distribution function for a discrete variable is given by:

$$F(x) = \sum_{i=m}^{n} f(x_i)$$

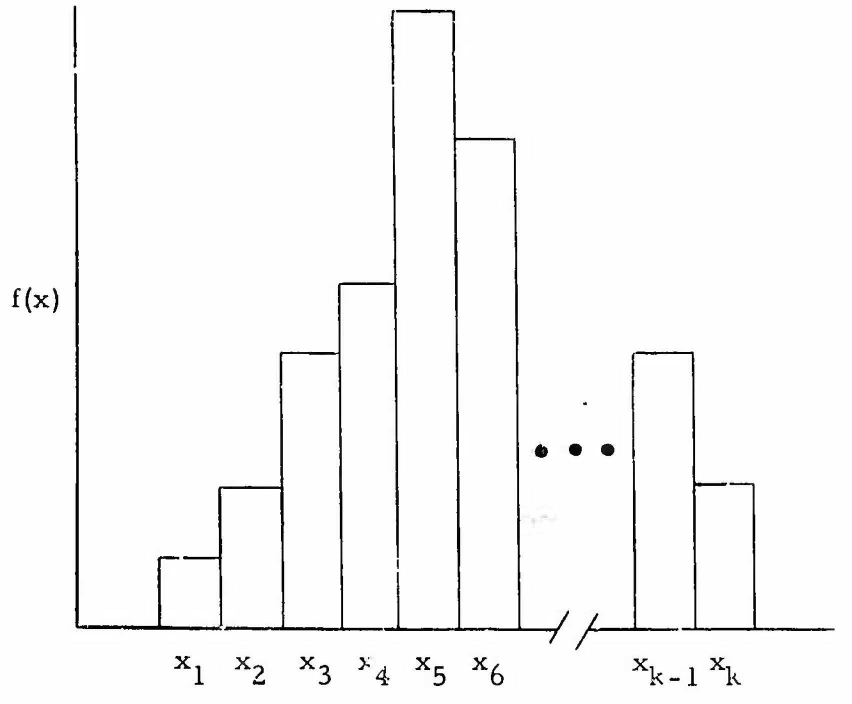


Figure 10-1. Density Function of a Discrete Variable

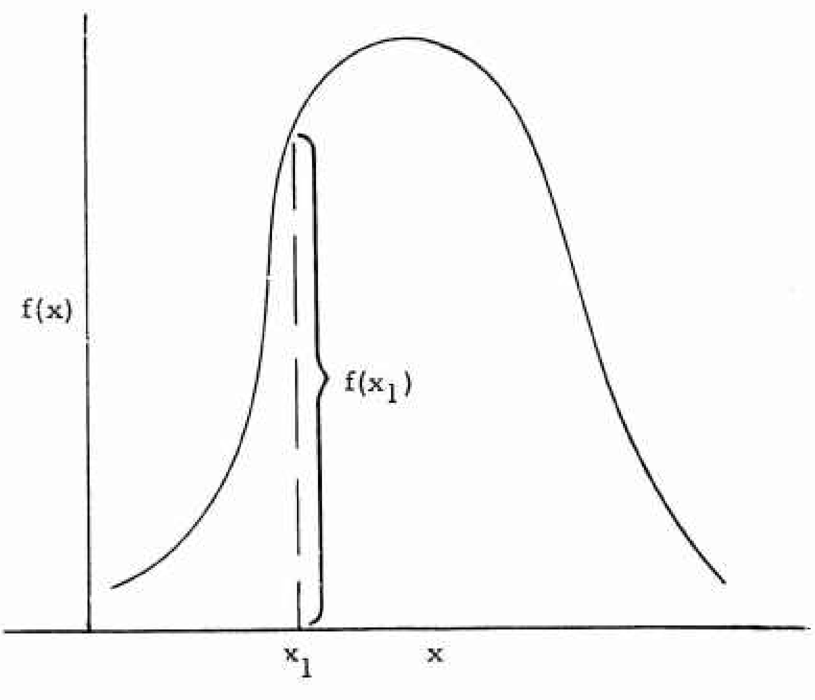


Figure 10-2. Density Function of a Continuous Variable

where:

m and n identify the values of x bounding the range of interest and $f(x_i)$ is the relative density function; i.e., $f(x_i)$ represents the ratio of the total number of elements having a value x_i to the total number of elements in the population.

In the continuous case, the distribution function is defined as the integral:

$$F(x) = \int_a^b f(x)\,dx$$

where:

f(x) is a density function such as that represented by the curve in Figure 10-2 and

a and b are the limits of the range under consideration.

The value of this integral will give the probability that a randomly selected value of the variable x falls within the range $a \leq x \leq b$.

These principles can be applied to the theory of reliability to obtain failure density and distribution functions. Suppose that at time $t = 0$, we have n items of identical age and failure distribution F(t). As items fail they are not replaced. Therefore, the expected number of failures by some time t_1 is:

$$n_f(t_1) = nF(t_1)$$

It follows that the expected number of items surviving to a time t_1 is:

$$n_s(t_1) = n - nF(t_1) = n[1 - F(t_1)]$$

and $[1 - F(t_1)]$ represents the probability of an item surviving until time t_1. This is also referred to as the reliability $R(t_1)$ of the item for time t_1.

The rate at which items fail can be defined as:

$$\frac{d}{dt}\left[nF(t)\right] = nF'(t) = nf(t)$$

where f(t) represents the failure density, and nf(t) represents the number of failures occurring during the next increment of time following time, t.

Another important relationship used in reliability measurement, the hazard rate h(t), is obtained as the ratio of the failure density function to the survival distribution such that

$$h(t) = \frac{nf(t)}{n[1 - F(t)]} = \frac{f(t)}{[1 - F(t)]}$$

This function gives the probability of failure during the increment of time following time t, assuming the item has survived until time t. The hazard rate is a function of the time already operated, and, in general, changes with time. In the particular case of the exponential distribution of failures, however, the hazard rate remains constant with time, and is identifiable as the failure rate of the item.

In summary, four basic functions are used in reliability measurement. These are:

(a) The failure density function f(t), which is the probability that an item will fail at a given time.

(b) The failure distribution function, given by:

$$F(t) = \int_{-\infty}^{t} f(t)dt$$

which is the probability that the item will fail before time t.

(c) The survival distribution function or reliability function is given by:

$$R(t) = 1 - F(t) = 1 - \int_{-\infty}^{t} f(t)\,dt = \int_{t}^{\infty} f(t)\,dt$$

which is a measure of the probability that the item does not fail before time t.

(d) The hazard rate function, given by:

$$h(t) = \frac{f(t)}{R(t)}$$

which is the probability that the item will fail in the increment of time following time t, given that it survives until time t.

In practice, specific functions must be substituted for the general functions in the above expressions. In reliability work, the most widely used functions are those associated with the exponential, Weibull and gamma distributions. These distributions are described briefly below in relation to their application to reliability measurement. Other distributions are also used in reliability measurement. However, only these three are discussed here as being representative of the application of statistical procedures to reliability problems.

2.2 The Exponential Distribution.

An exponential distribution is characterized by a constant instantaneous failure rate or hazard rate. The significance of this is that the average number of failures which occur in every time interval of a given length tends towards a constant. Physically, a constant failure rate indicates that the items have gone through a burn-in period so that the probability of failure due to "bugs" or inherent design deficiencies is reduced to a negligible quantity. Also, the system has not reached the point where physical wearout of components may result in an increasing failure rate.

The failure density function of a variable which has an exponential failure distribution is:

$$f(t) = \lambda e^{-\lambda t}$$

where the parameter λ is the constant failure rate and $\frac{1}{\lambda}$ or θ is called the Mean-Time-Between-Failures (MTBF). The failure density function has the value λ at $(t=0)$ and declines exponentially to zero as time approaches infinity.

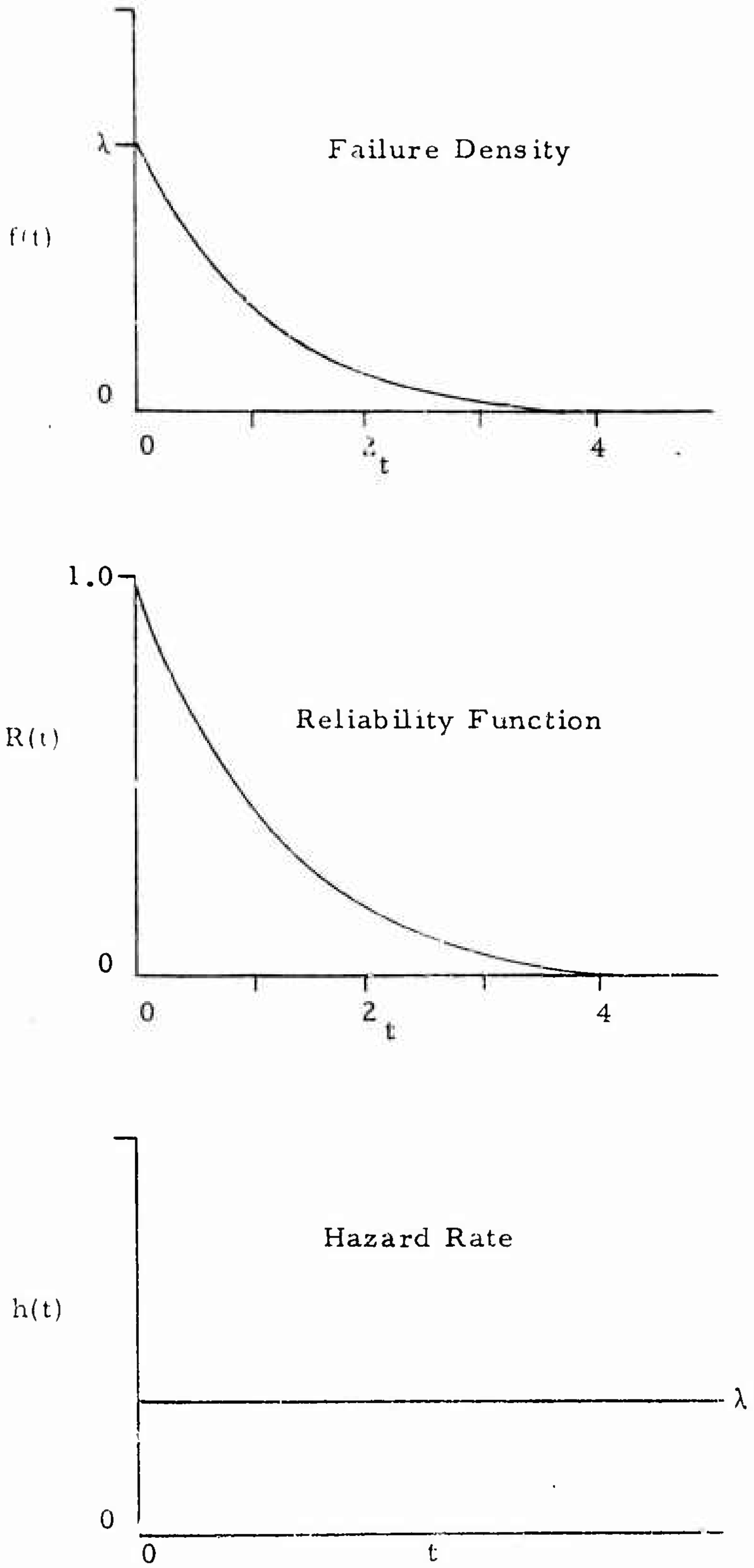
The reliability function is:

$$R(t) = \int_t^{\infty} \lambda e^{-\lambda t}\, dt = e^{-\lambda t} \qquad \text{for } t > 0$$

$$R(t) = 1 \qquad \text{for } t = 0$$

Hence, the origin of the term exponential failure distribution. The reliability function has the value $R(0) = 1$ and goes to zero asymptotically as t approaches infinity.

The mean of the exponential distribution is $(\frac{1}{\lambda})$ and the variance is $(\frac{1}{\lambda})^2$. The failure density function, reliability function, and hazard rate of a typical exponential failure distribution are shown in Figure 10-3.



Mean = μ = $(\frac{1}{\lambda})$

Variance = σ^2 = $(\frac{1}{\lambda})^2$

Figure 10-3. Failure Density, Reliability Function and Hazard Rate for the Exponential Distribution

The exponential distribution is characterized by a constant failure rate which is also the parameter of the distribution. If a system has survived to time t, the probability of survival for the next time interval of length t is the same as if it had just been placed into service. This assumption neglects degradation failures.

The exponential distribution is the most commonly used distribution in the design of equipment reliability tests, and is the basis of the reliability test plans presented in MIL-STD-781B. However, care should be taken in applying the exponential distribution because the failure distribution of a system consisting of units with exponential failure characteristics is not always exponential. The system failure distribution is exponential only if the system has no redundancy.

2.3 The Weibull Distribution.

A distribution that has been widely used in describing the reliability characteristics of electronic and electromechanical equipments and parts is the Weibull distribution. The Weibull distribution is capable of describing reliability functions characterized by failure rates that vary with time.

The Weibull failure density function is defined as:

$$f(t;\alpha,\beta,\gamma,) = (\beta/\alpha)(t-\gamma)^{\beta-1}\exp\left[-\frac{(t-\gamma)^{\beta}}{\alpha}\right] \quad \text{for } t \geq \gamma$$

$$\gamma \geq 0$$

$$\beta > 0$$

$$\alpha > 0$$

$$= 0 \text{ elsewhere}$$

The Weibull failure distribution function is:

$$F(t) = 1 - \exp\left[-\frac{(t-\gamma)^{\beta}}{\alpha}\right] \qquad \text{for } t \geq \gamma$$

$$\alpha, \beta > 0$$

$$= 0 \text{ for } t \leq \gamma$$

The three parameters in the equations are:

α = scale parameter, which normalizes the function with respect to the variable.

β = shape parameter, which determines the general characteristics of the function.

γ = location parameter, which locates the "starting point" of the function.

The shape and location parameters, β and γ, of the Weibull distribution are of particular interest in reliability measurement.

Values of β greater than 1 indicate that the failure rate increases with time, while values of β less than 1 indicate a decreasing failure rate. A special case in which $\beta = 1$ indicates a constant failure rate, in which case the Weibull distribution is equivalent to the exponential distribution. For example, the failure distribution function where $\beta = 1$ becomes:

$$F(t) = 1 - \exp\left[-\frac{t-\gamma}{\alpha}\right]$$

This indicates a distribution in which no failures occur until after a time equal to γ. If $\gamma = 0$, failures are possible at any time after time $t = 0$. The failure distribution, when $\beta = 1$ and $\gamma = 0$ becomes:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)\right]$$

Letting α equal $\frac{1}{\lambda}$ makes this exactly equal to the exponential distribution as discussed in paragraph 2.2.

The reliability function for the Weibull distribution is:

$$R(t) = \exp\left[-\frac{(t-\gamma)^{\beta}}{\alpha}\right], \qquad t \geq \gamma$$

$$R(t) = 1, \qquad t < \gamma$$

Letting $\beta = 1$ and $\gamma = 0$ provides the commonly used exponential reliability distribution.

The hazard rate function for the Weibull distribution is:

$$h(t) = (\beta/\alpha)\,(t-\gamma)^{\beta-1}, \qquad t \geq \gamma$$

Letting $\beta = 1$ gives $h(t) = \frac{1}{\alpha}$. Thus, the parameter $\frac{1}{\alpha}$ becomes equivalent to the failure rate λ of the exponential distribution.

Figure 10-4 shows a graph of Weibull density function, reliability function, and hazard rate function. Note, that as β increases the positive slope of the hazard rate function increases rapidly. This characteristic of the hazard rate function is the basis on which the Weibull distribution is frequently selected to describe the failure characteristics of mechanical parts subject to wearout failure.

2.4 The Gamma Distribution.

Several typical Gamma distributions are shown in Figure 10-5. The two parameter failure density functions for these distributions given by:

$$f(t) = \frac{1}{\alpha!\beta^{\alpha+1}} t^{\alpha} e^{-t/\beta} \qquad t > 0$$

$$= 0 \qquad t < 0$$

where the scale parameter $\beta > 0$ and the shape parameter $\alpha > -1$.

The failure distribution is given by:

$$F(t) = (1/\alpha!) \int_0^t \frac{x^{\alpha} e^{-x/\beta}}{\beta^{\alpha+1}} dx$$

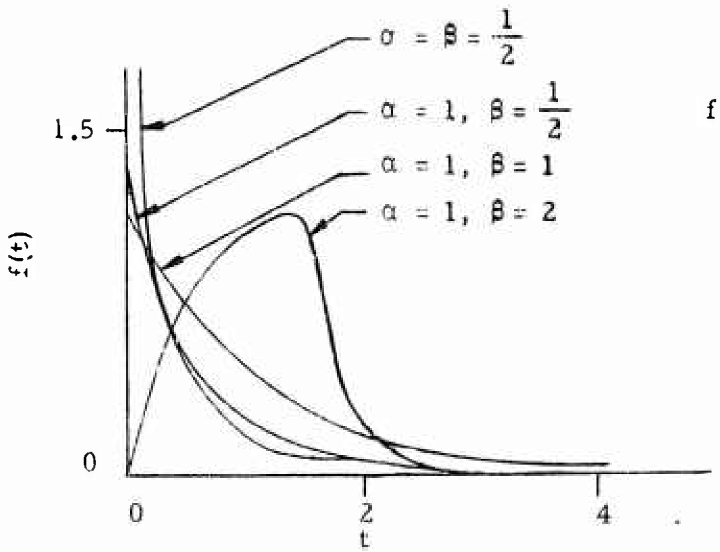
$$= (1/\alpha!)\, \Gamma[t/\beta(\alpha+1)]$$

where $\Gamma[t/\beta(\alpha+1)]$ is the incomplete gamma function as tabulated in Karl Pearson, Tables of the Incomplete Gamma Function, Cambridge University Press, London, 1922.

The population mean and variance are given as follows:

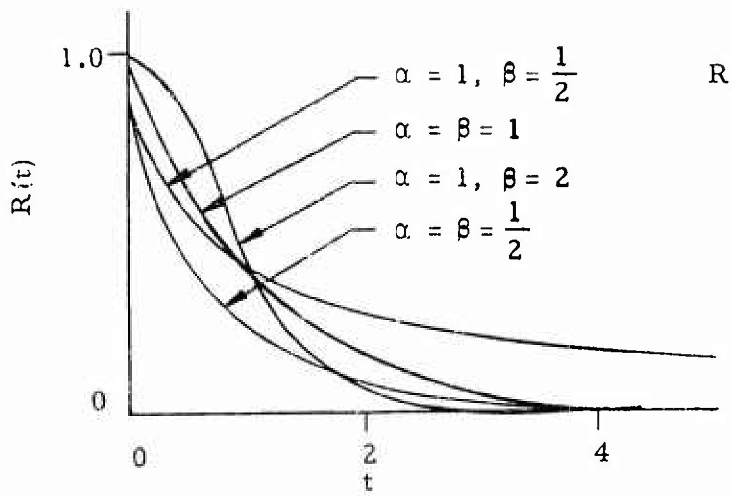
$$\mu = \beta(\alpha+1)$$

$$\sigma^2 = \beta^2(\alpha+1)$$

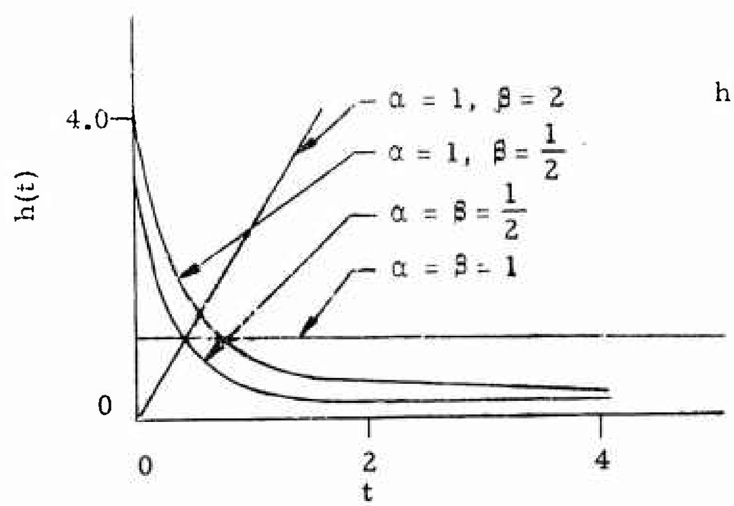


$$f(t) = \frac{\beta}{\alpha}\, t^{(\beta-1)} e^{-t^{\beta}/\alpha} \qquad t \geq 0,\ \alpha > 0,\ \beta > 0$$

$$= 0 \qquad t < 0$$



$$R(t) = e^{-t^{\beta}/\alpha} \qquad t \geq 0$$



$$h(t) = \frac{\beta}{\alpha} (t)^{(\beta-1)} \qquad t \geq 0$$

Figure 10-4. Failure Density, Reliability Function and Hazard Rate for the Weibull Distribution

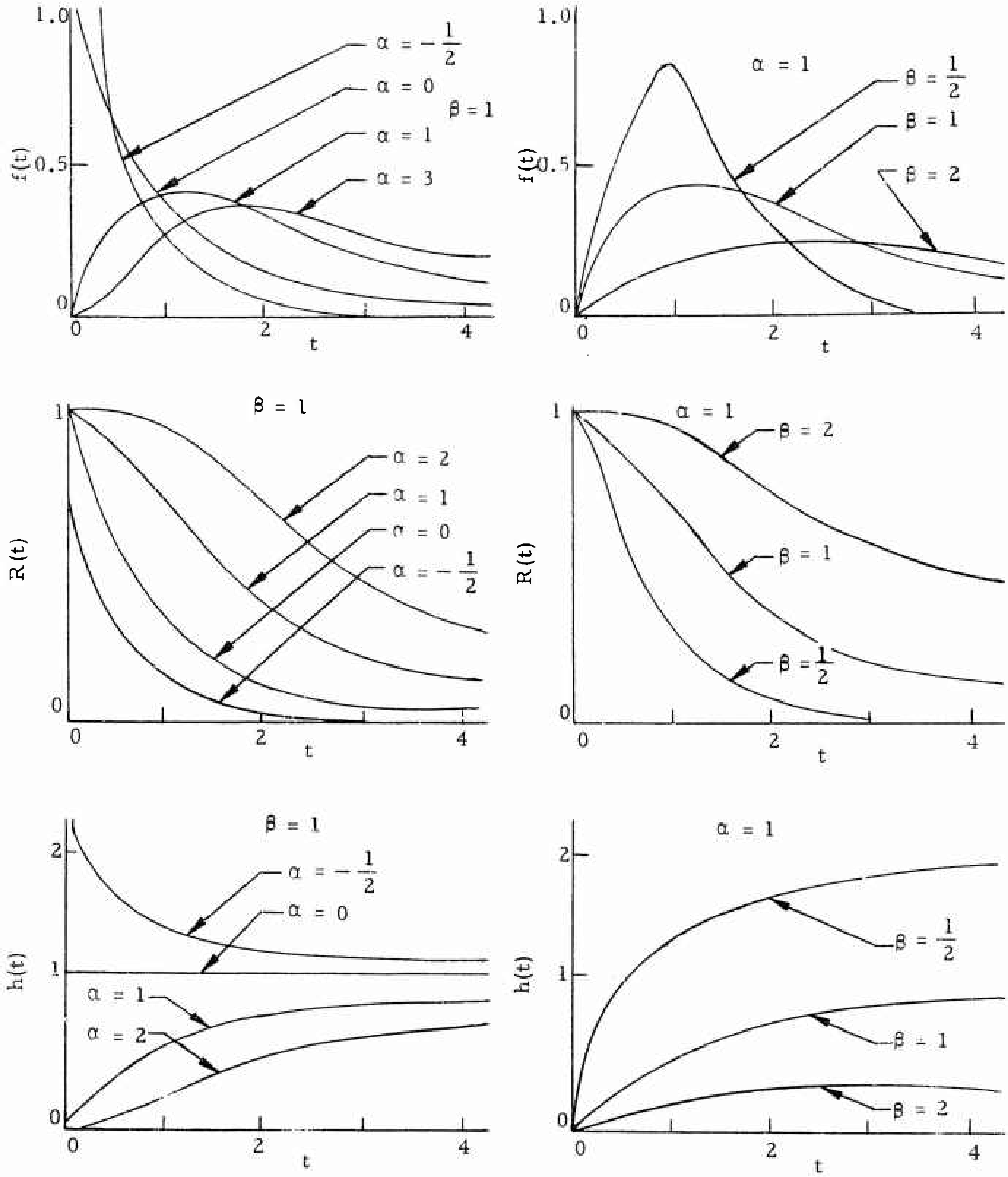


Figure 10-5. Failure Density Functions, Reliability, and Hazard Rate for the Gamma Distribution

The reliability is given by:

$$R(t) = \int_t^{\infty} \frac{1}{\alpha!\beta^{\alpha+1}} x^{\alpha} e^{-x/\beta} dx = 1 - \frac{1}{\alpha!}\Gamma[t/\beta(\alpha+1)], \quad t > 0$$

$$= 1 \qquad\qquad t = 0$$

The hazard rate is obtained from the expression:

$$h(t) = \frac{f(t)}{1 - F(t)} = t^{\alpha} e^{-t/\beta} \Big/ \int_t^{\infty} x^{\alpha} e^{-x/\beta} dx$$

The failure rate asymptotically approaches a constant value of $1/\beta$ with increasing time. As the parameter α decreases toward zero the failure rate at a given time increases toward $1/\beta$. The hazard rate is decreasing for $\alpha < 0$, and increasing for $\alpha > 0$.

The reliability function of the Gamma distribution displays an interesting behavior pattern. The reliability curve tends to have a flat top for larger values of α, that is, the reliability maintains at a high value for increasing (t) and decreases slowly. As α decreases the reliability tends to decrease towards zero more rapidly and at any given time the reliability is lower at a given time, for lower α. The Gamma distribution becomes the exponential distribution when $\alpha = 0$.

3. BAYESIAN STATISTICS IN RELIABILITY

3.1 Introduction to Bayesian Statistics.

Bayesian statistical procedures are based on the interpretation of probability as a degree of belief, i.e., the probability of an event A is a measure of the degree of belief one holds in the occurrence of the event A. Under this interpretation, probability may be directly related to the betting odds one would wager on the stated proposition. The statement that the probability is 0.75 (or equivalently, that the odds are three to one) that a specified change in the design will improve the reliability of a given product involves a degree of belief concerning the effect of the design change based on engineering judgement or experience. This differs from the "usual" frequency definition of probability which defines probability as follows: If an experiment is conducted

N times and a particular event A occurs n times then the limit of n/N as N becomes large is defined as the probability of the event A. Note in the design change example no experiment has been performed.

Thus, using Bayesian Techniques, subjective viewpoints (based on experience, guesses, etc.) can be quantified and treated under the rules of probability. Bayesian procedures rely on a theorem by Thomas Bayes called Bayes Theorem which allows the combination of probabilities (subjective) and experimental data. This theorem can be stated as follows:

{ The probability of event A_i, given observed data }

$$= \text{prior probability of } A_i \times \frac{\left\{\begin{array}{c}\text{Probability of Observed}\\ \text{Outcome Under Hypothesis}\end{array}\right\}}{\left\{\begin{array}{c}\text{Total Probability of Observed}\\ \text{Outcome Under All Possible}\\ \text{Hypotheses}\end{array}\right\}}$$

or in symbols:

$$P(A_i | B) = \frac{P(A_i)\, P(B/A_i)}{\sum_{j=1}^{n} P(B/A_j) P(A_j)}$$

where B is the observed outcome and A_i is the specific event whose probability is being calculated. The discrete probabilities above can be replaced by continuous functions. The left hand side of the equation is often called the posterior probability of A_i.

3.2 Use of Bayesian Techniques in Equipment Reliability Demonstration.

Bayesian procedures lend themselves for use during those stages of reliability programs when little test data are available, and when it would be desirable to combine "engineering judgement and experience" with the available test data to arrive at an estimate of the reliability of the equipment. The use of these procedures is described below. The purpose of the discussion is to illustrate the technique and not to give a detailed description of the procedure.

Assume that an engineer's prior estimate (based on inherent failure rate estimation or reliability prediction etc.) of the reliability of an equipment is .90. This information is encoded into a Bayesian framework by supplying a measure of the degree of belief that the reliability is .90. Techniques for doing this are omitted in this introduction. However, for the case where the test data are in the form of the number of equipments passing a given test, the prior information is encoded by specifying a number of assumed test trials and assumed test successes. If an engineer believed strongly in the prior reliability estimated he would use a large number of assumed test trials. If he did not have great faith in the prior estimate (diffuse prior) he would use a smaller number of assumed test trials. The number of assumed successes would be chosen so that the ratio of assumed successes to assumed test trials was equal to the prior estimate.

Hence, for encoding the .90 reliability above with a very strong belief one could use:

$$\text{Prior estimate of reliability} = \frac{\text{900 assumed successes}}{\text{1000 assumed trials}} = .90.$$

For a prior estimate whose validity was not as strongly believed one could use:

$$\text{Prior estimate of reliability} = \frac{\text{90 assumed successes}}{\text{100 assumed trials}} = .90$$

A still "weaker" prior would be encoded:

$$\text{Prior estimate of reliability} = \frac{\text{9 assumed successes}}{\text{10 assumed trials}} = .90$$

The effect of combining test data with these prior estimates can be illustrated by assuming that 19 out of 20 equipments pass a reliability test. The Bayesian expression for this case would be:

$$\text{Posterior estimate of reliability} = \frac{\text{number assumed successes} + \text{number observed successes}}{\text{number assumed trials} + \text{number observed trials}}$$

For the three above cases this yields:

$$P_1 = \frac{900+19}{1000+20} = .901, \quad P_2 = \frac{90+19}{100+20} = .909, \text{ and } P_3 = \frac{9+19}{10+20} = .933$$

The strongly believed priors were little affected by the test data while the weaker prior was changed. In general, the weaker the prior the less is its effect on the estimate for a given set of data. Notice in this case, P_3 is close to the estimate of 0.95 using the data alone.

This characteristic is even more apparent when the test results are far removed from the prior. For example, if there had been no observed successes in the above illustration, i.e., if 20 successive failures are observed, then:

$$P_1 = \frac{900}{1020} = .882, \quad P_2 = \frac{90}{120} = .75, \text{ and } P_3 = \frac{9}{30} = .30$$

The strong prior has been little changed by the data and a posterior estimate of .882 which is close to .90 is obtained in spite of 20 successive failures. In this case, P_3 is more strongly influenced by the estimate of zero successes based on the data alone.

Thus strong (non-diffuse) priors should not be used. In fact, if a strong prior is used there is no need for a test program since the test results are, in fact, ignored. On the other hand, diffuse priors "disappear" quickly in the presence of test data and estimates that agree closely with those based on the data itself. Weak priors, however, have certain advantages since they provide some basis of assessing reliability early in the program when little test data is available; they can be combined with observed results, thus avoiding estimates of 0 or 1 which are intuitively non-appealing (using data alone 5 out of 5 successes would yield a reliability estimate of 1.0), and thus allow the sequential combination of test results.

Let us consider another example using continuous distributions. An equipment is tested until 10 failures are observed. The tenth failure occurred after 1000 operating hours had been logged. We wish to obtain an estimate and a lower 95 percent bound on the mean life of the equipment using a prior distribution (degree of belief) of the parameter of the equipment failure distribution combined with the test data. The equipment MTBF requirement is 90 hours with a lower 95 percent bound on the mean life to be at least 70 hours.

The posterior probability of A_i as shown before is given by

$$P(A_i|B) = \frac{P(A_i)\ P(B|A_i)}{\sum_{j=1}^{n} P(B|A_j)\ P(A_j)}$$

and for continuous functions it is

$$P(A_i|B) = \frac{f(\lambda)\ P(t|\lambda)}{\int_0^\infty f(\lambda)\ P(t|\lambda)\, d\lambda}.$$

where:

$f(\lambda)$ is the density function of the prior distribution

$P(t|\lambda)$ is the density function of the observed outcome given λ

$\int_0^\infty f(\lambda)\ P(t|\lambda)\, d\lambda$ is the integral of the conditional densities weighted according to the densities of the respective prior. (Joint probability distribution)

λ is the parameter of the equipment failure distribution.

Assume that the equipment on test fails exponentially; that is, the failure density function $f(t)$ is given by

$$f(t) = \lambda e^{-\lambda t}$$

where:

λ is the constant failure rate

and our degree of belief that λ is of different magnitudes (the prior density) is given by a gamma density function $f(\lambda)$ with parameters $\alpha = 2.0$ and $\beta = .0025$.

The mean (μ_λ) of the prior is

$$\mu_\lambda = \beta(\alpha + 1) = .0025(3) = .0075$$

and the variance (σ^2) of the prior is

$$\sigma_\lambda^2 = \beta^2(\alpha + 1) = .00000625(3) = .00001875$$

The density function of the test data given λ is

$$P(t|\lambda) = \prod_{i=1}^{k} \left(\lambda e^{-\lambda t_i}\right) = \lambda^k e^{-\lambda T_k} = \lambda^{10} e^{-1000\lambda}$$

where:

λ is the parameter - a constant failure rate

k is the number of failures = 10

t_i is the i^{th} time-between failures

T_k is the sum of the k times between failures = 1000 hours

and the $\int_0^\infty f(\lambda)\, P(t|\lambda)\, d\lambda$

$$= \int_0^\infty \frac{1}{\alpha!\,\beta^{\alpha+1}} \lambda^\alpha e^{-\lambda/\beta} \lambda^k e^{-\lambda T_k}$$

$$= \frac{1}{\alpha!\,\beta^{\alpha+1}} \int_0^\infty \lambda^{\alpha+k} e^{-\lambda\left(\frac{1}{\beta} + T_k\right)} d\lambda$$

Making the transformation $\mu = \lambda\left(\frac{1}{\beta} + T_k\right)$

with $d\lambda = \dfrac{1}{\frac{1}{\beta} + T_k} d\mu$, $\lambda = \dfrac{\mu}{\frac{1}{\beta} + T_k}$

we obtain

$$\frac{1}{\alpha!\,\beta^{\alpha+1}} \int_0^\infty \left(\frac{\mu}{\frac{1}{\beta} + T_k}\right)^{\alpha+k} e^{-\mu} \frac{1}{\frac{1}{\beta} + T_k} d\mu$$

$$= \frac{1}{\alpha!\,\beta^{\alpha+1}} \left(\frac{1}{\frac{1}{\beta} + T_k}\right)^{\alpha+k+1} \int_0^\infty \mu^{\alpha+k} e^{-\mu} d\mu$$

$$= \frac{(\alpha + k)!}{\alpha!\beta^{\alpha+1}\left(\frac{1}{\beta} + T_k\right)^{\alpha+k+1}}$$

Thus the posterior density function $P(A_i|B)$ is given by:

$$P(A_i|B) = \frac{\frac{1}{\alpha!\beta^{\alpha+1}} \lambda^{\alpha} e^{-\lambda/\beta} \lambda^k e^{-\lambda T_k}}{\frac{(\alpha+k)!}{\alpha!\beta^{\alpha+1}\left(\frac{1}{\beta} + T_k\right)^{\alpha+k+1}}}$$

$$= \frac{\left(\frac{1}{\beta} + T_k\right)^{\alpha+k+1}}{(\alpha + k)!} \lambda^{\alpha+k} e^{-\lambda\left(\frac{1}{\beta} + T_k\right)}$$

which is a gamma density function with parameters

$$\beta^1 = \frac{1}{\frac{1}{\beta} + T_k} = \frac{1}{\frac{1}{.0025} + 1000} = \frac{1}{1400} = 0.0007142857$$

$$\alpha^1 = \alpha + k = 2. + 10. = 12.$$

The mean (μ_λ) of the posterior is

$$\mu_\lambda = \beta^1\left(\alpha^1 + 1\right) = 0.0007142857(13) = 0.0092857142$$

and the variance $\left(\sigma_\lambda^2\right)$ is

$$\sigma_\lambda^2 = {\beta^1}^2\left(\alpha^1 + 1\right) = 0.000000510204(13) = 0.00000663265$$

The mean (μ_λ) is the mean failure rate, the parameter of the exponential equipment failure distribution; hence its reciprocal is the mean life (μ) of the equipment.

$$\mu = \frac{1}{\mu_\lambda} = 107.7 \text{ hours}$$

A lower 95 percent bound on the mean life (μ) is equal to the reciprocal of an upper 95 percent bound on the mean failure rate (μ_λ). The upper 95 percent bound on the mean failure rate (μ_λ) is found by solving the following equation for $\mu_{\lambda_{UB}}$.

$$\int_0^{U_{\lambda_{UB}}} \frac{1}{(\alpha+k)!\left(\frac{1}{\frac{1}{\beta}+T_k}\right)^{\alpha+k+1}} \lambda^{\alpha+k} e^{-\lambda\left(\frac{1}{\frac{1}{\beta}+T_k}\right)} d\lambda = .95$$

$$\int_0^{U_{\lambda_{UB}}} \frac{1}{12!\,(0.0007142857)^{13}} \lambda^{12} e^{-\lambda/0.0007142857} d\lambda = .95$$

$$\mu_{\lambda_{UB}} = 0.0142295$$

Thus the lower 95 percent bound of the mean life (μ_{LB}) is

$$\mu_{LB} = \frac{1}{\mu_{\lambda_{UB}}} = 70.3 \text{ hours}$$

The Bayesian analysis indicates that the equipment meets the MTBF requirement of 90 hours with a lower 95 percent bound on the mean life of at least 70 hours.

The advantages of the Bayesian technique is that the test time and cost of an equipment reliability demonstration test can be reduced using the right prior. Investigations are presently being performed for determining typical priors for use in determining realistic posteriori distributions. For example the use of conjugate distributions as priors (i.e., the gamma distribution with the exponential, the beta distribution with the binomial, etc.) are being investigated for equipment reliability demonstration tests.

The disadvantage of the Bayesian technique is that the use of the wrong prior can lead to the wrong decision or an extremely lengthy test time where estimates are initially erroneous and which may not disappear until a substantial amount of test results are accumulated. This might not occur until late in the program and require major modifications whose need might have been apparent early had not Bayesian techniques been used. Thus, great care

must be taken in determining the form and parameters of the prior distribution (method of encoding information). Frequently, this is a difficult problem in that the subjective prior distribution may depend heavily on the past experience and prejudices of the person making the estimate. It has been suggested that a standard set of questions be established which would aid workers in defining the characteristics of the prior distribution. For example, the analyst might be requested to define the 0.01, 0.25, 0.5, 0.75, and 0.99 points of the subjective distribution. From this information the form and parameters of the prior distribution can be deduced.

3.3 Concluding Remarks.

The use of Bayesian procedures in reliability estimation techniques is new and controversial. Many statisticians do not accept as meaningful the subjective interpretation of probability which the Bayesian techniques utilize and hence argue the position that the probability statements are meaningless.

The above material has attempted to describe the procedures and how they might be used. Some of the advantages and disadvantages have been delineated. If one wishes to use such procedures, caution should be used and results should be closely monitored. In any case a more thorough technical description than is presented here should be consulted.

4. RELIABILITY TESTING

Reliability testing involves an empirical measurement of times-to-failure during equipment operation for the purpose of determining whether an equipment meets the established reliability requirements. A reliability test is effectively a "sampling" test in the same sense that it is a test involving a sample of objects selected from a "population". In reliability testing, the "population" being measured encompasses all failures that will occur during the life span of the equipment. A "test sample" is drawn from this population by observing those failures occurring during a small portion of the equipment's life.

In reliability testing, as in any sampling test, the "sample" is assumed to be representative of the population, and the mean value of the various elements of the sample (times-to-failure) is assumed to be a measure of the true mean (MTBF, etc.) of the population. It is recognized, however, that a certain amount of variability exists in

the population, and that it is unlikely for a randomly selected sample to have exactly the same mean as the population or a mean value quite different from the population mean.

Sampling errors in a reliability test cannot be avoided. However, the application of statistical techniques permits determining the probable magnitude of sampling error. Thus, the level of confidence that can be placed in the results of a reliability test can be quantified.

The following discussion illustrates, in a simplified manner, certain basic relationships between the various parameters of a reliability test.

4.1 Mechanics of a Reliability Test.

In any sampling test, conclusions are drawn based on the characteristics of a test "sample" which is selected at random from a "population". A sample in a reliability test consists of a number of times-to-failure, and the population is all the times-to-failure that could occur either from the one equipment or the more than one equipment on test. The test equipments (assuming more than one) are considered identical and thus their populations are also identical. Therefore a random sampling from one population or from all populations will produce the same statistical results. The sample is characterized by the mean value (θ_S) of all times-to-failure in the sample.[1]

If all possible samples of the same number of times-to-failure were drawn from the same or identical equipment, the resulting set of sample means would be distributed is some manner, as illustrated in Figure 10-6. The true MTBF (θ) of the equipment is not known, but sample means will be distributed around θ in some predictable manner.

Assume that one sample, having a mean θ_S is drawn from the distribution illustrated in Figure 10-6. This one sample mean is to be used to determine whether the population mean θ can be expected to be greater than some previously specified minimum

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[1] Other parameters, such as standard deviation, or variance are also used to describe a sample. However, only the mean is used here for convenience, and to be compatible with MIL-STD-781B, which considers only the one-parameter exponential distribution of failures.

acceptable value, θ_1. If the true mean were exactly equal to θ_1, then θ_1 could be substituted for θ in Figure 10-6. Also, θ_S could now be located at some point on the abscissa as shown in Figure 10-7.

The shaded area in Figure 10-7 represents the percentage of all samples that would have had a mean equal to or less than θ_S when the true mean is equal to θ_1. Also, the area marked β_S represents the percentage of samples that would have had a mean greater than θ_S. It could, therefore, be concluded that there is a probability of β_S percent that a sample selected at random from a population having a true mean equal to θ_1 will have a sample mean higher than θ_S. A more meaningful interpretation would be that after obtaining a sample mean of θ_S, there is a β_S percent chance that the equipment tested had a true MTBF as low as θ_1. The equipment could be considered to be within specifications providing β_S does not exceed the pre-specified acceptable level of consumer's risk.

4.2 Effect of Sample Size on Reliability Testing.

In the above discussion, the shape of the distribution curve was considered to be related to the selection of samples, each consisting of a given number of failures. Changing the sample size, however, will result in a change in the shape of the distribution curve. For example, if the sample size is increased, the sample means will tend to cluster more closely around the true MTBF, and the chance of sampling error will be reduced. The curves in Figure 10-8 illustrate two different distributions of sample means that could be drawn from the same equipment. The narrower curve represents the distribution of sample means when samples of larger size are drawn. The shaded areas under each curve represent the respective proportion of times the sampling error would be equal to $\theta_S - \theta_1$ or greater. The larger sample size would be much less likely to be in error by any given amount. Thus, greater precision in reliability testing will be realized as the number of times-to-failure observed during the test increases. Unfortunately, this greater precision can only be obtained at the expense of testing time and cost. Therefore, a trade-off area exists between testing precision and economy of testing.

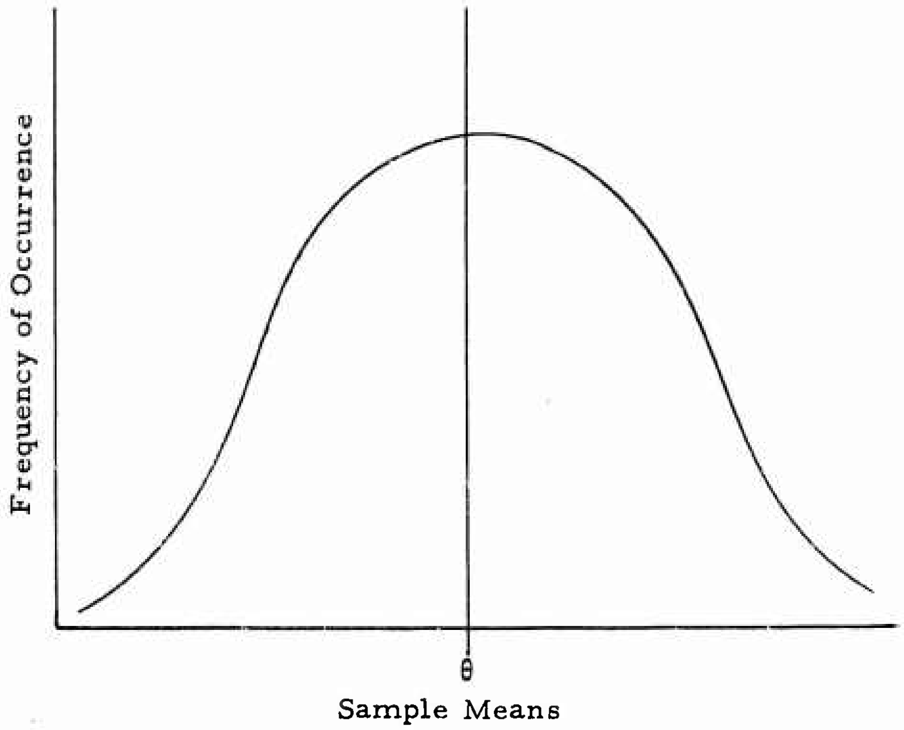


Figure 10-6. Frequency Distribution of Sample Means

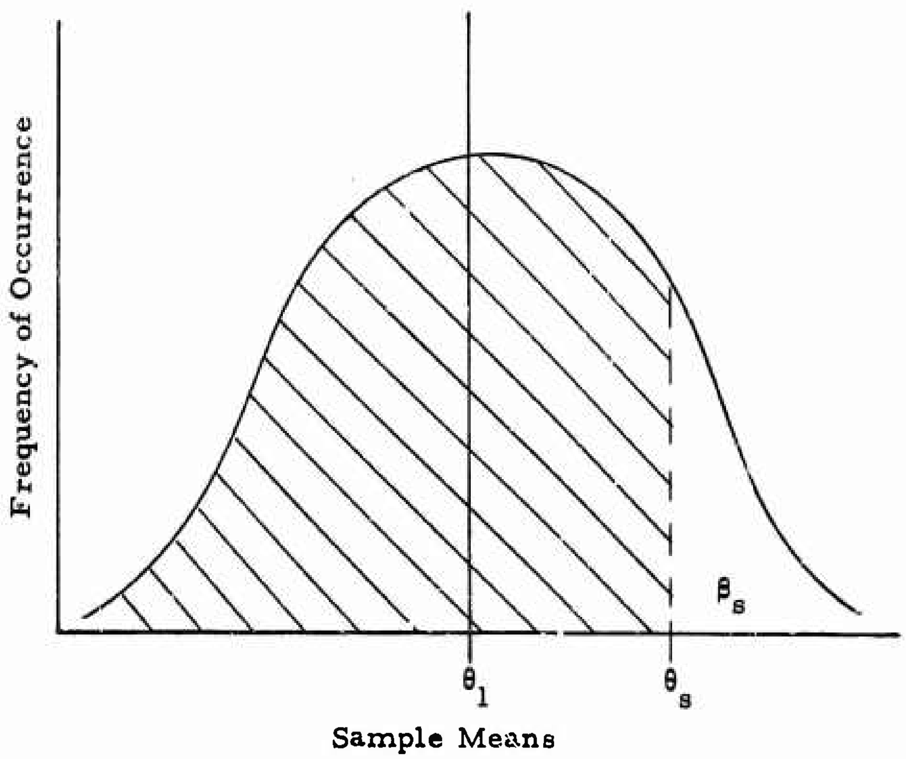


Figure 10-7. Sample Mean Located With Reference to θ_1

4.3 Minimum Acceptable MTBF (θ_1), Accept/Reject Criterion, and Consumer's Risk (β) Relationships.

Knowledge of the relationships between sample size and the expected distribution of sample means permits the development of test plans which include a pre-determined accept/reject criterion as a part of the plan. This criterion is effectively the value of a sample mean that should be obtained no more than some small percent of the time when a sample is drawn from an equipment having a true MTBF equal to the minimum acceptable value θ_1. For example, if the value β_S in Figure 10-7 represents the maximum level of risk that is to be assumed in accepting an equipment having a MTBF as low as θ_1, then the value θ_S would be established as the accept/reject criterion. If a sample mean obtained as a result of a reliability test were equal to or greater than this value, then the risk of accepting an equipment having a MTBF less than θ_1 would be less than β_S, and the equipment could be accepted.

For convenience, accept/reject criteria are usually stated either in terms of the number of failures occurring during a given operating time interval, or the time elapsing before a given number of failures occur. In either case, the number of failures and time interval combinations are equivalent to the θ_S value as discussed above. The accept/reject criteria are directly related to the minimum acceptable MTBF (θ_1), the acceptable level of "consumer's risk," (β), and the sample size.

However, knowledge of the variance of the time-to-failure distribution is not usually known prior to test. One option is to utilize the exponential distribution assumption of the variance equal to the mean. This assumption will provide conservative results if the actual time-to-failure distribution has an increasing rather than constant failure rate. Another option is to use the test data to provide an estimate of the mean and variance, in which case the accept/reject criterion cannot be determined in advance of the test.

4.4 Producer's Risk (α) and Producer's MTBF Goal (θ_G)

Consideration of the relationships between minimum acceptable MTBF (θ_1), consumer's risk (β), and sample size, as discussed above, will permit the customer (Air Force) to control the risk

being taken in testing to assure that the product is acceptable. However, there is also the risk to the producer of having a truly acceptable equipment rejected.

It is possible that sampling error will produce a sample having a mean less than the accept/reject value and, therefore, cause rejection, even though the true MTBF of the equipment is greater than the minimum acceptable value. This possibility is illustrated in Figure 10-9. The left-hand curve in this figure represents the distribution of sample means when the true MTBF is just equal to the accept/reject value. In this case, there is a 50 percent chance of having the product rejected due to sampling error. This chance, or risk of rejecting an acceptable equipment, is represented by the shaded area designated α_1. The risk of rejecting a "good" equipment will be less, however, if the equipment MTBF is greater than the accept/reject value. The shaded area designated α_2 in Figure 10-9 represents the probability of rejecting an equipment having a true MTBF greater than the accept/reject value. It is apparent that this risk will be reduced as the true MTBF and/or the sample size is increased.

To assure the acceptance of his equipment, the contractor establishes a reliability goal that is somewhat higher than the accept/reject value. This MTBF goal (θ_G) is selected such that, if the equipment MTBF is truly equal to θ_G, the risk of the equipment being rejected due to sampling error will be not greater than some pre-established producer's risk (α).

This risk (α) can be reduced, either by increasing θ_G with respect to the accept/reject value, or by increasing the sample size. However, the latter alternative also affects the relationship between the accept/reject criterion and the minimum acceptable MTBF (θ_1), as discussed in paragraph 4.3. In determining a test plan, the two risks (α and β) are usually pre-established to be equal.

4.5 Combined Characteristics of a Reliability Test Plan.

In practice, a reliability test must satisfy two objectives. First, it must assure the government that an unacceptable equipment is rejected. However, the contractor must also be assured that an acceptable equipment is not rejected. Since 100 percent assurance of meeting either objective is not possible in any practical case, both the government and the contractor must be willing to assume some degree of risk in designing and performing the test.

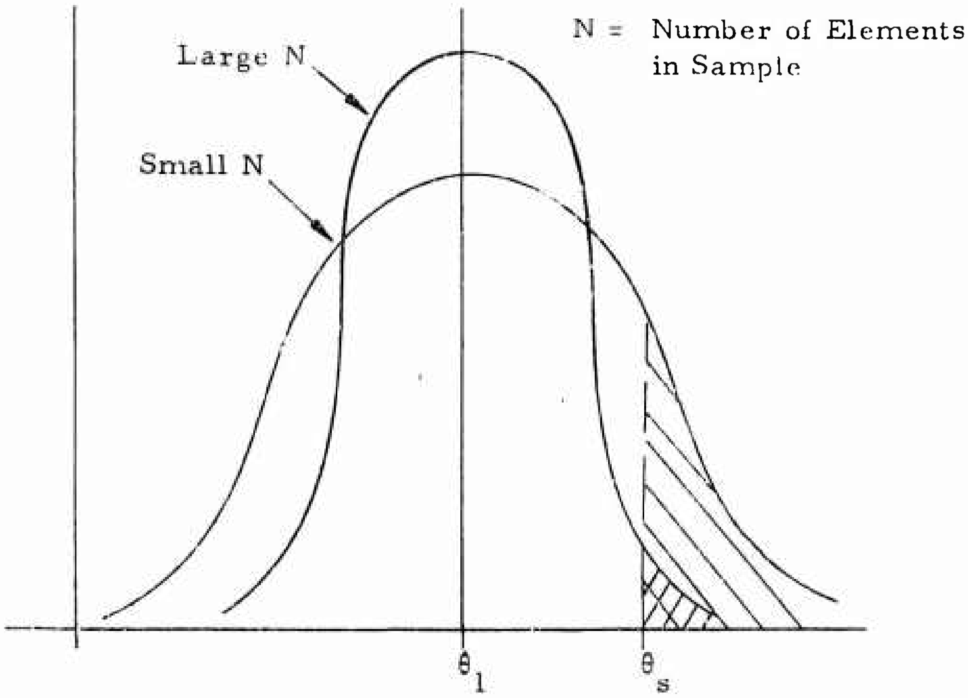


Figure 10-8. Distribution of Sample Means for Large and Small Sample Sizes.

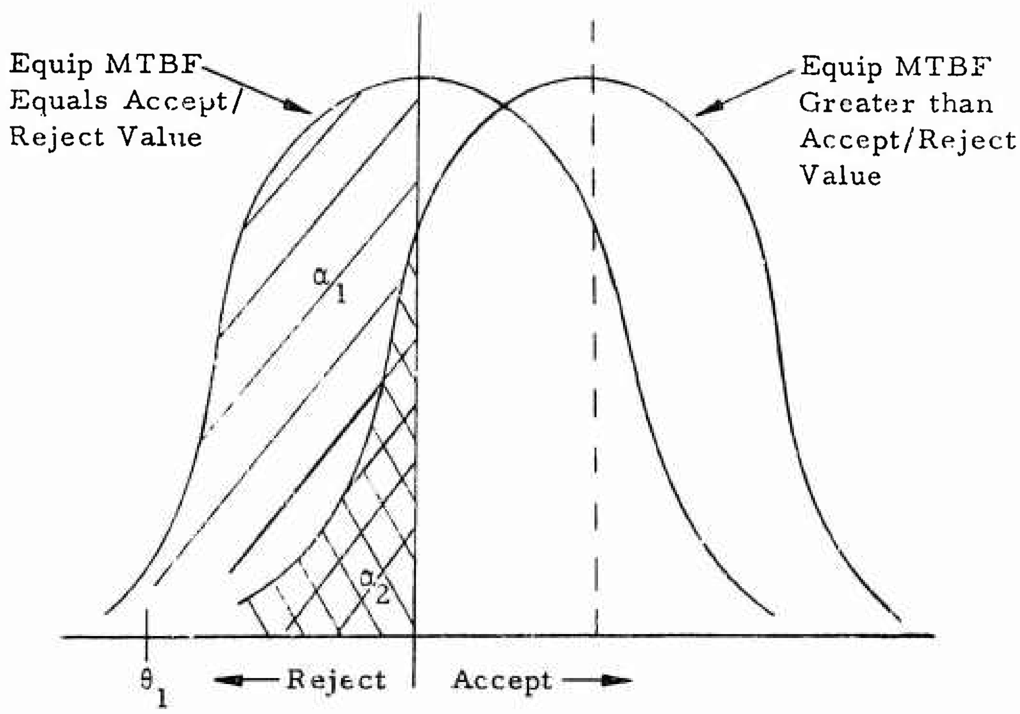


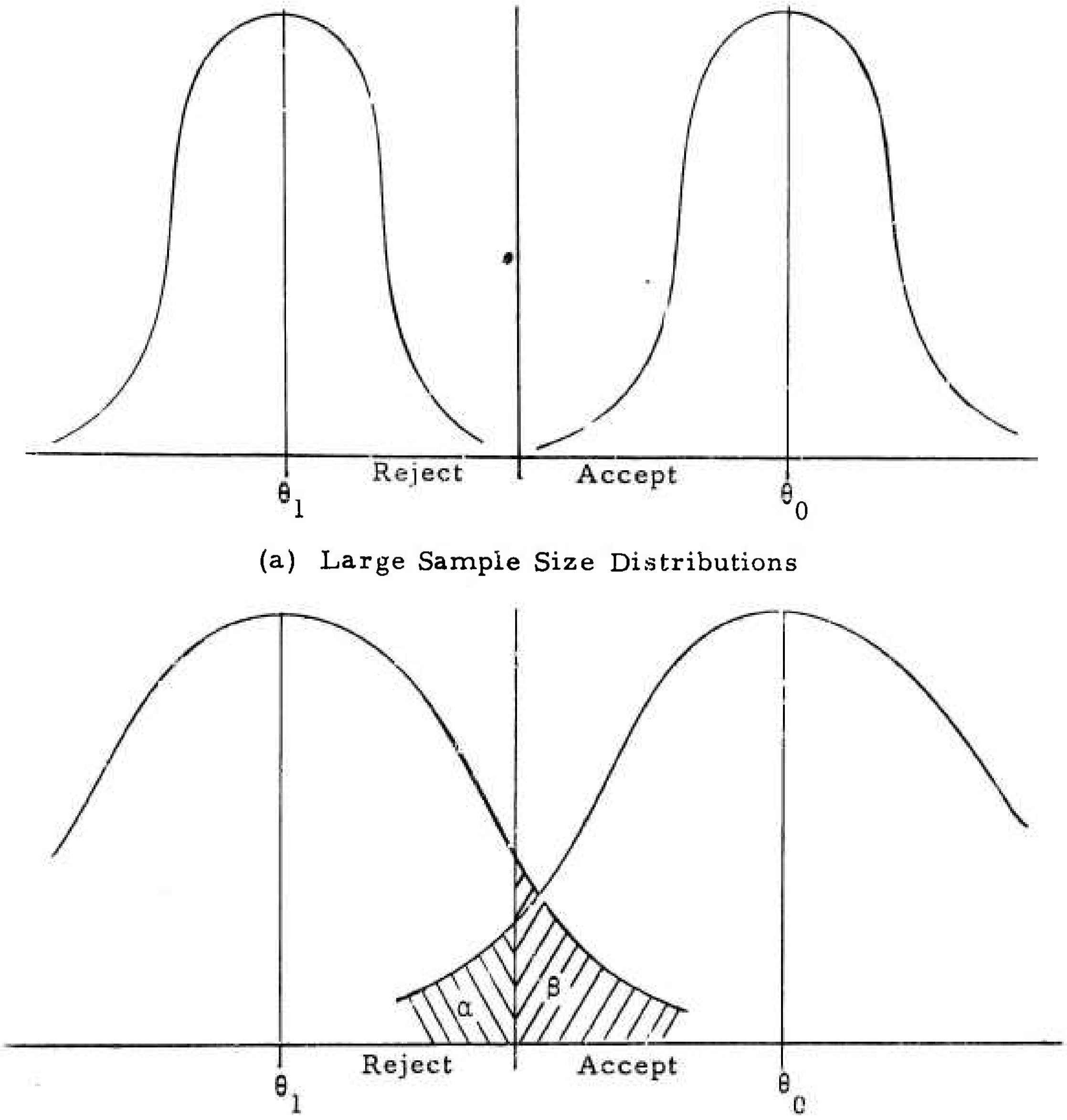
Figure 10-9. Distributions of Sample Means Drawn From Truly Acceptable Equipments

The Government establishes a minimum acceptable MTBF (θ_1) and accepts some risk (β) in verifying whether the achieved MTBF is truly greater than (θ_1). On the other hand, the Government has an MTBF requirement (θ_0), but because of test time, schedule, dollars, etc. limitations, the Government is willing to accept a demonstrated θ_1. It is with respect to the MTBF requirement that the Government specifies a contractor risk (α) of having his equipment rejected, even though the design requirement, θ_0, is achieved. The two values, θ_1 and θ_0, and the corresponding risks, β and α, are directly related because the results of a reliability test will be evaluated with respect to only one accept/reject criterion as shown in the test plans in MIL-STD-781B. This relationship is primarily a function of the distribution of sample means and, thus, is directly influenced by the number of failures and variances of the times-to-failure obtained in the test. Of course, the contractor sets his own design goal θ_G which is usually around θ_0 according to a cost/risk/profit evaluation he makes.

The basic relationships to be considered in test plan design can be illustrated by considering two hypothetical equipments, one having a MTBF at exactly the minimum acceptable value, θ_1, and the other exactly meeting the design requirement, θ_0, which is greater than θ_1. Also, the true MTBF of either equipment is not known, but a reliability test is to be performed to distinguish between the acceptable and unacceptable equipment. The problem is to select a sample size such that the test will discriminate between the two equipments with only an acceptable level of risk of making incorrect decisions due to sampling error.

By selecting a sufficiently large sample size, the distribution of sample means from the two equipments could be made to appear as illustrated in Figure 10-10(a). In this case, there would be almost no ambiguity concerning the particular equipment from which the sample was drawn. This plan would readily discriminate between the two equipments, with negligible risk of incorrect decision due to sampling error.

A test plan that provides this degree of discrimination is usually impractical because it usually requires a prohibitively large sample size for the ratio of θ_0 to θ_1 that was established. Therefore, in most reliability tests, the sample size is usually set as low as possible to reduce testing cost and time requirements by specifying the maximum acceptable α and β risks that can be associated with θ_0 and the smallest acceptable θ_1 respectively.



(a) Large Sample Size Distributions

(b) Effect of Reducing Sample Size

Figure 10-10. Characteristics of Reliability Test Plans

The effect of reducing the sample size is illustrated in Figure 10-10(b). Here, θ_1, θ_0, and the accept/reject value are the same as in Figure 10-10 (a), but the sample size has been reduced, thereby broadening the distribution curves as shown. The areas designated α and β represent the resulting producer's and consumer's risks, respectively. The effect of a significant decrease in θ_1 will be a significant decrease in the β risk and a decrease in the α risk whereas, the effect of an increase in θ_1 will be the opposite. The effect of a significant increase in θ_0 will be a significant decrease in the α risk and a decrease in the β risk, whereas the effect of a decrease in θ_0 will be the opposite.

As indicated by the preceding discussion, the risks involved in a reliability test are affected by sample size, the relationship between θ_1 and θ_0, and the accept/reject criterion. Therefore, the design of a reliability test involves the consideration of the relationship between the various parameters and, to the extent possible, to minimize the risk, cost and time requirement.

In practice, the sample size is often specified in terms of a fixed number of equipment failures. Alternately, however, the test time can be fixed, and the sample size will be the number of failures occurring during this time interval.

The relationship between θ_1 and θ_0 is usually stated in terms of the "discrimination ratio", θ_0/θ_1. This parameter is applicable when the individual times-to-failure of the equipment are exponentially distributed. Other distributions will require the consideration of other parameters, such as the variance or standard deviation in relating θ_0 to θ_1.

The accept/reject criterion is usually stated in terms of a specific number of failures occurring during the duration of the test. Some accept/reject criteria are stated in terms of a maximum allowable number of failures during a fixed time interval, while others are stated in terms of a minimum time permitted before a fixed number of failures occur. In either case, the criterion corresponds to a particular MTBF value falling between θ_1 and θ_0.

In most Air Force procurement programs, reliability test plans are designed using MIL-STD-781B, Reliability Tests, Exponential Distribution. This standard provides data suitable for designing test plans when the exponential distribution of failures can be assumed. Other sources of sampling plan data are available for application when distributions other than exponential are expected. Some of these sources are mentioned in paragraph 8 of this chapter.

Some considerations in the application of MIL-STD-781B in the design of reliability test plans are presented in the following paragraphs.

5. RELIABILITY TEST PLAN DESIGN

The Air Force is responsible for establishing the initial reliability requirement, and the desired degree of assurance that this requirement is met. The contractor must then establish his design goals and develop a test program that verifies achievement of these goals to the satisfaction of the Air Force, and at acceptable risk and minimum cost to the contractor. All of these factors are interrelated and must be considered in the design of a test plan. In general, a reliability test plan is defined by establishing the minimum acceptable MTBF (θ_1), the consumer's risk (β), and the specified MTBF (θ_0), the producer's risk (α), and the accept/reject criterion. The latter parameter relates total test time to observed failures and, therefore, effectively establishes the sample size.

In general, reliability tests performed under Air Force contract are designed in accordance with the provisions of MIL-STD-781B, "Reliability Tests: Exponential Distribution". This standard provides a series of test plans, test levels, and procedures applicable to electronic equipment reliability testing where the exponential failure distribution can be assumed. The application of this standard involves the performance of a series of tasks in establishing the test plan parameters. The following paragraphs contain data and discussions to aid in the application of MIL-STD-781B.

5.1 Establishing the Minimum Acceptable MTBF (θ_1).

The minimum acceptable MTBF (θ_1) is a value determined by the Air Force to be the minimum level of MTBF that can be tolerated. Any equipments having a MTBF less than θ_1 are considered unsatisfactory. This value should be carefully selected, and should reflect the reliability allocations performed in developing the System Specification. Also, consideration should be given to the risk of inadvertently accepting an unacceptable equipment due to the inherent variability of a reliability test. It should be noted that reliability test plans with consumer's risks (β) of less than 10% of accepting a true MTBF equal to θ_1 are usually not practical. Therefore, if any uncertaintly exists, θ_1 values are usually selected in a somewhat conservative manner.

5.2 Establishing the Consumer's Decision Risk (β).

The degree of risk that the Air Force is willing to assume in accepting an unacceptable equipment should be established at the time θ_1 is established. This risk, which is measured in terms of the probability (β) of accepting an equipment having a true MTBF equal to θ_1, is chosen depending on the importance of achieving the specified level of reliability, and on the practicability of test plans that would provide given risk levels.

MIL-STD-781B provides reliability test plans having β's ranging from 10% to 40%. (Test plans having β's as low as 1% are available in other sources such as Handbook H108.[2] However, economic and time limitation factors usually prohibit the use of the lower risk levels.) A point of departure for establishing a β value can be obtained by considering the general relationship between this parameter and the subsequent reliability test time requirements of MIL-STD-781B test plans. For example, the approximate ranges of expected test time for commonly used test plans having a discrimination ratio of 1.5:1 are: (See paragraph 5.3.)

β	Expected test time in multiples of MTBF)
.10	17 to 30
.20	8 to 14
.30	3 to 5

Based on this, it is apparent that a reduction in the risk level can cause a significant increase in test time which will, in turn, impact on testing costs and schedules.

The expected test time can be reduced by careful design of the reliability test. In general, however, a firm β risk is specified at the time θ_1 is established, and prior to the development of the other parameters of the test plan. Thus, β cannot be readily "manipulated" in designing the test plan.

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[2] Handbook H108, Sampling Procedures and Tables for Life and Reliability Testing (based on Exponential Distribution), Office of the Assistant Secretary of Defense (Supply and Logistics).

5.3 Establishing the Specified MTBF (θ_0) and Producer's Decision Risk (α).

The minimum acceptable MTBF (θ_1), and consumer's risk (β) are normally established by the Air Force as discussed above. Based on these and other considerations the Air Force usually selects the Test Plan to be used. It is then the responsibility of the contractor to develop efficiently and economically conducted reliability tests that will assure verification of achieved reliability without degrading the risk level established by the Air Force. Before the test plan can be developed, however, the specified MTBF (θ_0) and the producer's risk (α) must also be established.

The specified MTBF (θ_0) is the MTBF requirement specified in the detailed equipment specification, and must be established prior to beginning the detailed design engineering activities. Furthermore, θ_0 is directly related to θ_1 and β, as well as to the producer's risk (α). Therefore, the reliability test plan must be considered, at least in a preliminary sense, in establishing θ_0.

The specified MTBF (θ_0) is established as a given multiple of the minimum acceptable MTBF (θ_1) such that the ratio between these two values is equal to a desired "discrimination ratio". This parameter (θ_0/θ_1) is also selected based on the number of equipments, test time (i.e., tolerance time), and funds available. In general, however, a practical value of θ_0/θ_1 can be established based on the specified consumer's risk (β), and by considering the approximate test time that will be available. Table X-1 provides a rough estimate of the relationship between θ_0/θ_1, α, β, and test time for test plans specified in MIL-STD-781B. The values in this table are not precise but will provide a guide for considering the related parameters in establishing an appropriate θ_0/θ_1 value. The final value is established by the Air Force after making careful trade-off between θ_0/θ_1 and α, and considering the constraints imposed by the pre-established minimum acceptable MTBF (θ_1) and consumer's risk (β).

It should be noted that, once established, the θ_0/θ_1 value cannot readily be changed. This is because θ_0/θ_1 effectively fixes θ_0 with respect to the specified θ_1. Furthermore, θ_0 typically is used by the contractor as the "design center" for the Detailed Specifications and, therefore, must remain firm throughout the detailed design program.

Table X-1. Relationships Between Discrimination Ratio θ_0/θ_1 and Expected Time for Reliability Testing

α	β	θ_0/θ_1	Expected Test Time (Multiples of MTBF)
10%	10%	1.25	100
		1.5	17 - 30
		2.0	5 - 14
		3.0	2 - 3
		5.0	0.7
10%	20%	1.25	72
		1.5	20
		2.0	6
		3.0	2
20%	20%	1.25	44
		1.5	8 - 14
		2.0	2 - 4
		3.0	1.5
30%	30%	1.25	15
		1.5	3 - 5
		2.0	1.3 - 1.8
		3.0	0.4
35%	40%	1.25	5

The other parameter, α, defined by the Air Force is the risk contractors are willing to accept with the test plan. This value is tentatively established when θ_0 is determined. Determination of the test plan should be based on the final trade-offs involving consideration of relationships between α, test time (or sampling procedure), and accept/reject criteria within the constraints of the previously fixed θ_0/θ_1 and β values.

5.4 Selecting the Reliability Test Plan.

In general, a test plan is defined by establishing the decision risks (β and α), discrimination ratio (θ_0/θ_1) and the accept/reject criteria. MIL-STD-781B defines 30 test plans for reliability testing. Three of these, test plans XXVI, XXVII, and XXVIII are special purpose fixed length test plans for reliability demonstration, production verification, and longevity testing, respectively, in which the decision risks are not defined, and which provide a semi-quantitative or qualitative evaluation of equipment reliability. The demonstration and production verification tests (XXVI and XXVII) consider only a "specified" MTBF and assume the operating characteristics of Test Plan I in the stated accept/reject criteria. The longevity test (XXVIII) is entirely qualitative, and is intended to permit an evaluation of patterns and causes of failures occurring over an extended operating period. Test Plan XXIX is an equipment screening test not used for reliability demonstration.

The remaining 26 Test Plans (I through XXV) provide a selection of Probability Ratio Sequential Tests (PRST), short run high risk PRST, and fixed length tests applicable to reliability tests such as those performed during Category I or Category II test programs.

5.5 Establishing the Accept/Reject Criteria.

Specific accept/reject criteria are specified in MIL-STD-781B for each test plan. Therefore, the accept/reject criteria for a reliability test is fixed with the selection of the test plan.

In general, the accept/reject decision is based on the number of failures observed during a test, and the total operating time. For fixed length tests, the decision is based on the number of failures occurring before a pre-established operating time. The accept/reject decision for a PRST test, however, is based on experience accumulated during the test. The test is continued until a clear-cut decision can be made based on the total operating time before a given number of failures occur. As each failure occurs, the accumulated operating time is observed, and a decision is made to either

accept, reject, or continue testing until the next failure occurs. This process is repeated for each failure in sequence until a decision to either accept or reject is made. If the decision cannot be made before some pre-determined time, the test is terminated and a decision is made as if the test were a fixed length test.

In addition to the quantitative accept/reject criteria stated in MIL-STD-781B, a test plan must also state the manner in which the test time is accumulated during a test, and should precisely define "failures" as applicable to the test. In general, failures are defined as "the inability of a previously acceptable item to perform its required function within previously established limits". However, details involving failure criteria must be stated for the specific equipment under test.

The test time is the total time the equipment is actually operated during the test. This time is usually accumulated by more than one equipment, in which case the test time is the sum of the operating time accumulated by all equipments included in the test. MIL-STD-781B specifies general procedures for determining the quantity of equipments for a test. However, specific requirements for selecting the "test sample" should be specified as part of the reliability test plan.

6. RELIABILITY TEST LEVEL

The reliability tests of MIL-STD-781B are performed under specified conditions of temperature and temperature cycling, on-off cycling, input voltage cycling, and mild vibration to simulate some of the more common stresses of the actual operating environment. A particular combination of such stresses defines a "test level" to be maintained during a reliability test.

MIL-STD-781B outlines ten test levels that are considered as minimum requirements for equipments intended for various applications. These standardized test levels should be modified as necessary to correspond to any extreme or unusual environmental conditions for which the equipment is being designed. In cases where specific environmental requirements have not been specified, the following test levels are suggested:

Test Level A-1: Fixed ground equipment intended for permanent or semi-permanent installation in air conditioned buildings, and which will be operated continuously (e.g., operations room equipments).

Test Level A: Mobile or semi-portable ground or shipboard equipment to be installed in an air conditioned shelter, and which will be operated intermittently.

Test Level B: Similar to Test Level A, except applicable to non-air conditioned environment in which the ambient temperature can reach a high of 40°C (104°F). When higher temperatures are anticipated, Test Level C, (50°C) or Test Level D (65°C) may be specified in lieu of Test Level B.

Test Level E: Airborne Equipment or other equipment expected to be operated intermittently under rapidly varying ambient temperatures. Test Level E includes temperature cycling within the range of - 54°C (- 65°F) to + 55°C (+131°F). More extreme temperature ranges are simulated by Test Level F (-54°C to + 71°C), Test Level G (- 54°C to + 95°C), Test Level H (- 65°C to + 71°C), and Test Level J (- 54°C to + 125°C).

7. PART RELIABILITY TESTING

The preceding discussions have been concerned with reliability testing of equipments to determine whether a specified reliability requirement has been met. Another type of reliability test is that of testing parts to determine the failure rate of parts that are being selected for use in Air Force equipments. In general, part testing differs from equipment testing in that tests are performed on test samples consisting of a number of parts selected at random from large production lots. Sampling plans for such tests can be designed using the standard procedures of MIL-STD-105D, "Sampling Procedures and Tables for Inspection by Attributes."

The procedure for part reliability testing is essentially the same as the procedure for any attribute sampling inspection. The only difference is that sample items are tested for life or survival instead of some other property. Therefore, the probable distribution of part failures must be considered in selecting sampling plans from MIL-STD-105D. A procedure and related table of factors for adapting the MIL-STD-105D sampling plans to acceptance sampling inspection when the item quality is reliability is presented in Quality and Reliability Assurance Technical Report TR7.[3] This document

[3] Quality and Reliability Assurance Technical Report TR7, Factors and Procedures for Applying MIL-STD-105D Sampling Plans to Life and Reliability Testing, Office of the Assistant Secretary of Defense (Installations and Logistics) Washington, D.C. 20301.

considers the Weibull distribution, together with the exponential distribution as a special case, as the underlying statistical model.

The procedures described in TR7 for performing past reliability tests involve the following general steps:

(a) A suitable sampling inspection plan is selected from MIL-STD-105D, using tables and factors provided in TR7.

(b) A random sample of items of the size specified by the selected MIL-STD-105D plan is drawn from the production lot.

(c) The sample of items are tested (operated) for the specified period of time t.

(d) The number of items that failed during the test is compared with the number of failures allowed under the selected MIL-STD-105D plan.

(e) If the number of failures is equal to or less than the acceptable number, the lot is accepted as meeting the reliability requirement. If the number of failures exceeds the acceptable number, the lot is rejected.

In adapting the MIL-STD-105D sampling plans to reliability testing, the usual Acceptable Quality Level (AQL) is related to a dimensionless ratio $100t/\mu$. This ratio relates the required mean life of a lot (μ) to a specified test truncation time (t). With reliability test plans selected in terms of these ratios, the probability of acceptance will be high for lots whose mean life meets the specified requirement.

Because of the complexity of the procedures in Technical Report TR7, and because of the necessity for frequent referral to specific data in MIL-STD-105D, a detailed discussion of part reliability testing procedure will not be presented in this notebook. Complete information concerning application of the procedure is presented in TR7 together with some practical examples which demonstrate methods for evaluating the effectiveness of a proposed test plan, as well as procedures for designing reliability test plans.

In general, test plans are designed using a table that equates AQL levels to the portion of a lot that would have a life equal to or less than some time t, relative to the mean life (μ) of the lot, when the item lives follow Weibull distributions having various shape parameters. Once established, the equivalent AQL values permit reliability test plans to be designed in the same manner as any MIL-STD-105D test plan.

Certain precautions should be observed in interpreting data resulting from part reliability tests. A reliability test is conducted by operating each of a number of parts for a time duration that is short in relation to the specified acceptable mean life. The results of the test are evaluated with reference to the number of failures occurring during the test. Conclusions concerning the mean life of the lot are based on an assumed distribution of part lives.

None of the parts in the test sample are actually operated as long as the acceptable mean life. Therefore, the reliability test does not provide a measure of the true mean life or failure rate of the part in question. It does, however, provide a given degree of assurance that the mean life of a particular lot is not less than a specified value, and that a large number of such lots will not contain more than some small percentage (given by the AQL) of unacceptable parts.

8. RELIABILITY TEST PLAN DATA

The following documents contain alternate sampling procedures and tables applicable to reliability test plan design.

a. Sampling Procedures and Tables for Life and Reliability Testing Based on the Weibull Distribution (Mean Life Criterion). Quality Control and Reliability Technical Report TR3, Office of the Assistant Secretary of Defense (Installations and Logistics), Washington, D. C.

b. Sampling Procedures and Tables for Life and Reliability Testing Based on the Weibull Distribution (Hazard Rate Criterion). Quality Control and Reliability Technical Report TR4, Office of the Assistant Secretary of Defense (Installations and Logistics), Washington, D. C.

c. Sampling Procedures and Tables for Life and Reliability Testing Based on the Weibull Distribution (Reliable Life Criterion). Quality Control and Reliability Technical Report TR6, Office of the Assistant Secretary of Defense (Installations and Logistics), Washington, D. C.

d. Factors and Procedures for Applying MIL-STD-105D Sampling Plans to Life and Reliability Testing, Quality and Reliability Assurance Technical Report TR7, Office of the Assistant Secretary of Defense (Installations and Logistics), Washington D. C.

e. Sampling Procedures and Tables for Life and Reliability Testing (Based on Exponential Distribution). Quality Control and Reliability Handbook (Interim) H108. Office of the Assistant Secretary of Defense (Supply and Logistics), Washington, D. C.

f. Tests for the Validity of the Assumption that the Underlying Distribution of Life is Exponential. Office of the Assistant Secretary of Defense (Supply and Logistics), Washington, D. C. (This serves as a companion document to H108.)

g. Sampling Procedures and Tables for Inspection by Attributes, MIL-STD-105D.

CHAPTER 11

RELIABILITY IMPROVEMENT

1. INTRODUCTION

Reliability improvement includes a variety of engineering and design techniques specifically directed toward either achieving a higher level of reliability than previously had been achieved, or increasing the assurance that an established level of reliability will be achieved. In the basic context, reliability improvement activities are concerned with developing a system that is less vulnerable to unavoidable reliability problems.

Reliability problems can be identified as resulting from two fundamental sources: failure of the material from which the system hardware is constructed, and failure or error on the part of the human element of the system. These can be defined in terms of identifiable causes, such as physical stresses that cause material failure, and operational demands that contribute to human error. In some instances it is possible to eliminate or reduce a particular stress or level of operational complexity to the point that significant failure or errors no longer occur. In general, however, it is more practical to identify and counteract rather than to eliminate or reduce a cause of unreliability. For example, it is more common to assure that an item is capable of withstanding a given stress than to reduce the stress.

Five distinct but interrelated areas are considered in reliability improvement. The most elementary of these is that of assuring that piece parts from which the system will be constructed are capable of reliable operation under given stress levels and operational environments. The correlary of this identifies the second area: i.e., assuring that the operational and environmental stresses to be encountered do not exceed those for which the parts are designed. In the event of discrepancy between piece part capability and use demands, a third area of reliability improvement is available. This makes use of techniques such as derating to reduce the effect of relative stress levels and provide a safety margin and corresponding improvement in system reliability. Additionally, the techniques of redundancy provide means for achieving an even greater improvement in system reliability by providing alternate means for achieving success. Also, consideration of factors contributing to operational error can aid in reducing the effect of the human element in unreliability.

2. INDIVIDUAL PART RELIABILITY

System reliability is a direct function of the reliability of each of the individual parts making up that system. Improvement in overall reliability, therefore, requires consideration of the reliability of the individual parts, and recognizes the true cause of unreliability, i.e., the vulnerability of equipment function to individual part failure. Thus, the first consideration in reliability improvement is that of assuring that the individual parts are capable of performing at the required level of reliability.

2.1 Part Failures

A part is considered to have failed when the operational characteristics of the part have changed until the system operation is no longer satisfactory. Within this definition, part failures can be divided into two general categories. The first category involves a relatively gradual change in functional characteristics of the part until tolerance limits are exceeded. The second category involves abrupt and drastic changes in functional characteristics. These two categories of failure are often called "tolerance" failures and "catastrophic" failures, respectively. These terms refer to the abruptness of failure, and not to the relative effect on equipment operation. In fact, within the meaning of the terms as used here, catastrophic part failures need not have catastrophic effects on system performance, and, conversely, the fact that certain failures are referred to as tolerance failures does not preclude their having catastrophic effects on the system's performance.

Although tolerance and catastrophic failures may be similar in their effects on system performance, there is often considerable difference in their underlying causes, or mechanisms of failure. Therefore methods of reducing failures of the catastrophic type and thereby improving reliability, may be different than methods of reducing failures of the tolerance type.

Tolerance failures are typically caused by "wear out" or "drift" phenomena, and concern the respective part itself. Reduction of such failures is most often accomplished by improvement of the failure rate or drift rate of the part in question. Some improvement also can be achieved by reducing the vulnerability of the equipment to variation in part characteristics. Catastrophic failures, on the other hand are usually the result of thermal, electrical, or mechanical stresses. In most cases it is necessary to reduce such failures by employing specific equipment design features to "protect" the part in question. A thorough understanding of certain relationships between part reliability and equipment reliability will aid in recognizing the degree of reliability improvement that can be obtained by reducing part failure.

2.2 Part Reliability vs. Equipment Reliability

An electronic equipment is a collection of parts physically and electrically joined together in such a manner that, collectively, they perform a desired function or functions. If an equipment is capable of satisfactorily performing its functions at some point in time, it will continue to have that capability until a significant change occurs in the operating characteritsics of some part, or a group of parts within the equipment. Conversely, if the equipment fails, a part or group of parts within the equipment will have failed. Therefore, it is apparent that equipment reliability is a function of the number of failures of individual parts within the equipment.

The specific relationship between part reliability and equipment reliability is usually complex and is dependent on many factors, including the functional configuration of the equipment and the application of redundancy (alternative functions in the event of failure). For example, an equipment having redundant parts will not fail until all redundant parts have failed. In a case such as this, the relationship between part and equipment reliability cannot be defined until the functional configuration of the equipment is defined.

In the most elementary case, however, an equipment would not include redundant parts, and each part failure would result in an equipment failure. If simultaneous failures were impossible, it is apparent that the total number of equipment failures during a given period of time would be equal to the sum of all individual part failures during the same time period, such that:

$$F_t = F_1 + F_2 + \ldots + F_n$$

where

F_t = the total number of equipment failures during a given interval of time

$F_1, F_2, \ldots, F_n$ = the respective total numbers of failures of each of the n parts in the equipment during the same interval of time.

This additive relationship between total part failures and total equipment failures is independent of the distribution of failures with time (i.e., pattern of failure) and, therefore should provide a simple method for relating part reliability to equipment reliability. However, it is usually more meaningful to evaluate

part reliability in terms of failure rate rather than total failures and thereby provide a measure that is independent of any specific interval of operating time. In the general case, a simple relationship does not exist between part failure rate and total number of failures due to a general tendency for failure rate to change with time. In many practical cases, however, use can be made of the fact that the failure rates of individual parts remain essentially constant over extended periods of time. Thus, the total number of failures expected to occur during any time interval can be calculated as the product of the failure rate and the duration of the time interval of interest. In such cases, the distribution of failures with time can be described by the exponential distribution function, such that the reliability of a part is related to its failure rate as follows:

$$R(t) = e^{-\lambda t}$$

where

$R(t)$ = the reliability (probability of survival) of the part over time t.

λ = the failure rate of the part

t = the time period of interest

The reliability of a series system of several parts is equal to the product of the reliabilities of the individual items, such that:

$$R_s(t) = R_1(t) . R_2(t) . . . R_n(t)$$

where

$R_s(t)$ = the reliability of the series system over time t.

$R_1(t), R_2(t) . . . R_n(t)$ = the respective reliabilities of each of the n parts making up the system.

If all failures are exponentially distributed, i.e., all parts have constant failure rates, this last expression becomes:

$$R_S(t) = e^{-\lambda_1 t} . e^{-\lambda_2 t} . . . e^{-\lambda_n t},$$

where $\lambda_1, \lambda_2, \ldots, \lambda_n$ are the respective failure rates of the individual items. This expression can be re-written:

$$R_s(t) = e^{-t(\lambda_1 + \lambda_2 + \ldots + \lambda_n)}$$

The quantity $(\lambda_1 + \lambda_2 + \ldots + \lambda_n)$ is equivalent to the sum of the failure rates of all parts in the system. A quantity λ_s, equal to the sum of the individual part failure rates, can be substituted in this expression, such that

$$R_s(t) = e^{-\lambda_s t}$$

Thus, the reliability of a series system made up of several items, each having a constant failure rate can be evaluated by considering the effective failure rate of the overall system to be equivalent to the sum of the failure rates of the individual parts making up the system.

Most practical systems do not take on a simple series configuration such as that discussed above. However, in virtually all cases, a system can be divided into fundamental sub-elements that can be considered individually as simple series systems for evaluation purposes.

It is interesting to note that an additive relationship between part failure rates and equipment failure rates can often be used, even though some parts do not exhibit a constant failure rate. For example, suppose one part in an equipment exhibits a non-constant failure rate, but does show a number of distinct time intervals, throughout which the failure rate is substantially constant. If the failure rate of this part over the time interval t_1 is λ_1, over the time interval t_2 is λ_2, etc., then the reliability of this part over the time interval t where $t = t_1 + t_2 + t_3 + \ldots$ is:

$$\begin{aligned} R(t)_i &= e^{-\lambda_1 t_1} \cdot e^{-\lambda_2 t_2} \cdot e^{-\lambda_3 t_3} \ldots \\ &= e^{-(\lambda_1 t_1 + \lambda_2 t_2 + \lambda_3 t_3 + \ldots)} \\ &= e^{\frac{-t(\lambda_1 t_1 + \lambda_2 t_2 + \lambda_3 t_3 + \ldots)}{t}} \\ &= e^{-t\lambda eq} . \end{aligned}$$

where

$$\lambda eq. = \frac{\lambda_1 t_1 + \lambda_2 t_2 + \lambda_3 t_3 + \ldots}{t}$$

Thus, the average failure rate of the part over the total time interval can be used as the equivalent failure rate, $\lambda eq.$ This value can now be combined with the failure rates of other parts as if it were constant.

The foregoing discussion has been presented to indicate a fundamental relationship between equipment reliability and part reliability, i. e., that a basic additive relationship exists between individual part failure rate and total equipment failure rate, while a basic multiplicative relationship exists between individual part reliability and equipment reliability. These relationships provide the foundation for the reliability models by which reliability improvement requirements are defined and evaluated. Furthermore, assessment of the relative influence of individual part reliability on equipment reliability aids in identifying reliability problem areas and provides a means for evaluating the relative worth of planned reliability improvement actions.

3. IMPROVING PART RELIABILITY

As previously discussed, system or equipment failures are a direct result of part failures. Therefore, a fundamental aspect of reliability improvement should be that of assuring that individual parts are appropriately reliable before expending excessive time and funds in developing failure counteracting schemes. This implies two different, but related areas of activity: (1) selecting types of parts that are capable of meeting the reliability requirements and assuring that individual parts actually included in the hardware are capable of performing as specified; and (2) employing methods such as derating to obtain a "safety margin" for parts in use.

3.1 Part Selection for Reliability Improvement

Part selection involves two areas of activity. The first concerns the initial selection of the type of part to be used in the end item. This involves close cooperation between design engineering and reliability engineering activities to:

a. Identify all reliability-critical electrical stresses, temperature extremes, and mechanical stresses associated with the item in which the part under consideration is to be used, and

b. Evaluate the specifications for alternative types of parts to identify the type that will best withstand these stresses.

In the selection of parts it is often advisable to consider alternate classes of parts in order to obtain a significant improvement in reliability. For example, dramatic reliability improvement through the application of solid state devices has been demonstrated in the recent application of microelectronics. The proper use of microelectronics not only results in the obvious reduction of the size and weight of electronic equipment, but it also provides considerable control over and improvement of the reliability of equipment. In fact, microelectronics have been used extensively for the primary purpose of achieving high reliability in cases where the other factors such as reduction of size and weight were not specified as design objectives.

The second part selection activity involves preconditioning procedures for detecting and eliminating defective or "weak" parts from production lots. The selection of potentially reliable types of parts does not assure the reliability of parts actually used.

A recent survey of available test and operational data from typical microelectronic devices, for example, indicates failure rates for similar devices ranging from 0.05 failures per million hours to well over 1.0 failures per million hours. This wide range of failure rates has not been related to device type, but is primarily dependent upon the effectiveness of the manufacturer's processing, inspection and manufacturing controls.

When reliability achievement is a critical factor in system development, parts cannot be used "as received" from the manufacturer. Regardless of the manufacturer's quality control program, some defective or substandard parts are possible in any production lot. Therefore, a "pre-conditioning" process for detecting and eliminating substandard parts is an essential reliability improvement activity. The basic pre-conditioning process consists of screening and pre-aging to remove weak and defective items from manufacturer's lots consisting primarily of good quality items, and burn-in (also called aging) either before or after installation in the equipment as a basis for final selection. The burn-in can be under simulated end-use conditions or accelerated environments.

Figure 11-1 depicts the pre-conditioning process within the life cycle of the items. The elimination of "manufacturing freaks" that would exhibit earlier failures than those expected from the product (i.e., screening) requires testing under stresses that are precisely controlled so that weak items are discovered without damaging good items.

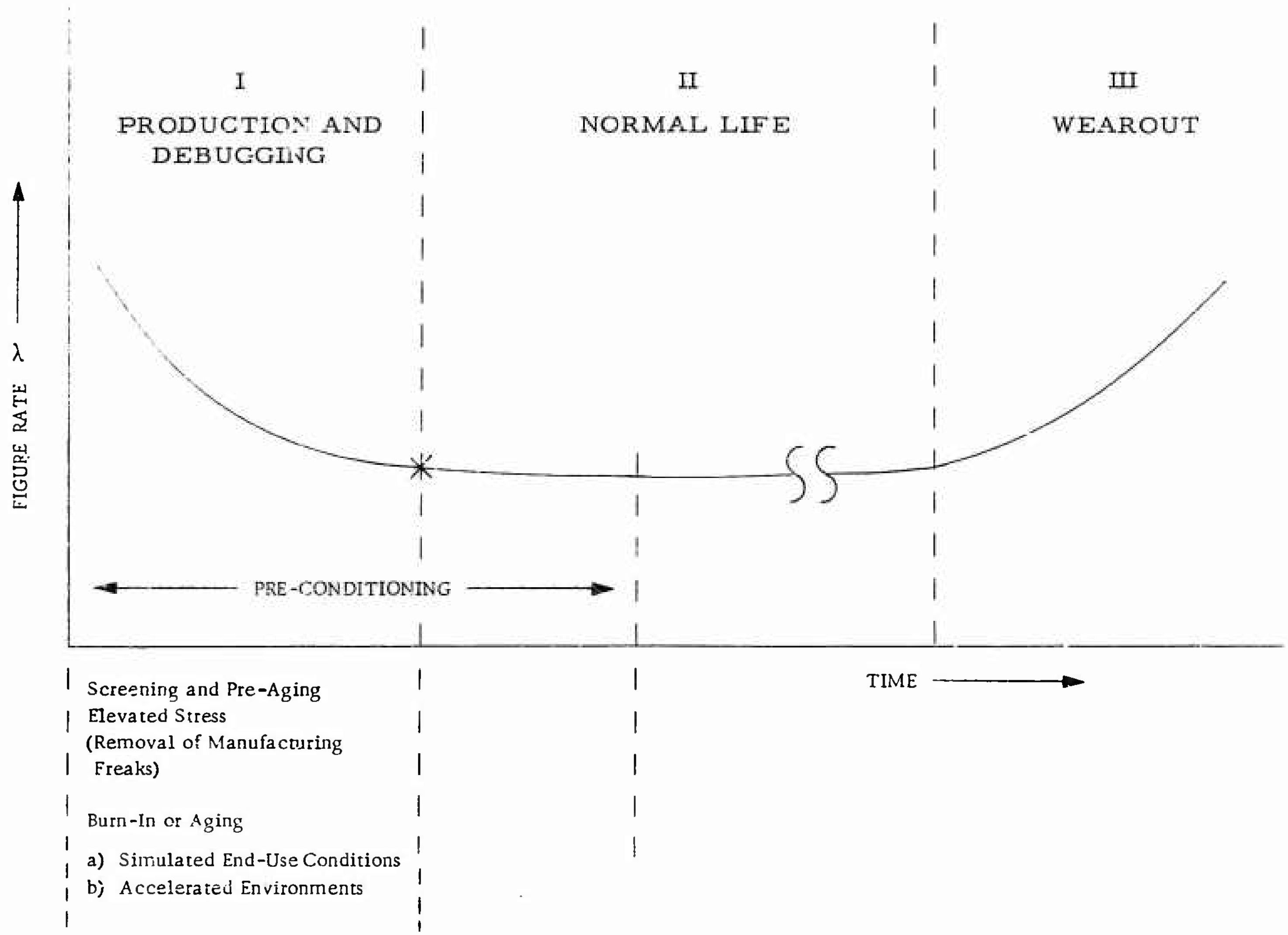


Figure 11-1. Pre-Conditioning Process

Screening in this manner identifies many items that would otherwise go undetected, and therefore effectively increases the reliability of the end item. Further improvement can be realized by also including a "burn-in" process which consists of preliminary operation of the item under real or simulated use, or accelerated environmental conditions, in order to encourage early failure of weak items.

3.2 Selection of Non-Standard Parts

To properly control the extensive and complex part procurement activity, the Air Force maintains a standardization program which requires that parts meet military specifications and standards. Documents such as the established reliability specifications not only control functional and physical characteristics of parts, but also establish appropriate part reliability. Therefore, standardized parts meeting military established reliability specifications will exhibit a stated level of reliability. Many parts, however, are not covered by military specifications and standards. Such "non-standard" parts, are either too limited in application to warrant the preparation of military specifications, or are too newly developed for military specifications to have been established. Reliability information on non-standard parts is often limited to the extent that supplementary data will be required before the part can be accepted for use. Therefore, the selection of non-standard parts often requires reliability assurance procedures that may be more involved than those used in selecting standard parts.

The most dependable, as well as the most usable, part reliability information is obtained from well conceived and carefully monitored reliability tests. Other data sources, such as manufacturer's data and past performance data, may also be utilized, but the validity of such data may be questionable, and usually provides only a qualitative indication of the reliability of the part for the application under consideration.

For non-standard parts having a history of past applications, and where information has been logged carefully and is sufficiently extensive to yield failure data at required levels of confidence, a usable reliability prediction can be made. It is essential when

using such data, however, that the applications referred to in the data should be as nearly similar to the contemplated applications as possible. Also the stipulated electrical characteristics of the part for which the performance data are available should fairly closely resemble the part under consideration. Unfortunately, however, those application details that have been recorded are rarely available in exactly the form required, and any reliability prediction based on them should be used with the knowledge that there may be differences between the part under consideration and the part used in generating the data.

The most meaningful reliability data for non-standard parts are derived from well designed and accurately monitored reliability tests, the results of which should be carefully analyzed to determine failure rate or reliability characteristics. Reliability data, however, are only as sound as the tests from which they are drawn. Several reliability testing procedures are available for application in the selection and acceptance of non-standard parts.

The most common and meaningful reliability test is the time-oriented (life test) type. However, strength oriented and degradation oriented types are also useful. The latter types do not provide a quantitative evaluation of actual reliability of the part, but they do help provide a safety margin for unexpected stress peaks and are valuable when it is economically unfeasible to determine the actual value with a time-oriented test.

Time-oriented reliability life tests involve operation of the part under stresses as close as possible to conditions of actual operation. The part is permitted to operate in this fashion for a predetermined time or until failure occurs. Following failure, the test is continued using another part of the same type until a pre-determined test time or number of failures has been experienced. The test is then halted and the failure rate is calculated by statistical analysis of the test data.

Time-oriented life tests can be classified as follows:

a. Nonvariate or static life tests, which involve operating the part under one set of stress conditions for a predetermined time period. Most tests in this category are performed as rating verification tests to provide assurance that the part at least meets minimum life requirements. As such, the tests seldom provide the true failure rate of the part. Determining failure rates in this manner would require either excessively large sample sizes or long periods of test time.

b. Univariate life tests, which measure the life of a device under varying levels of stress. A critical stress such as temperature is varied in a step-stress technique to obtain time-to-failure vs. stress level patterns. A variation of this technique involves application of a controlled, continuously increasing stress. These tests are particularly useful for delineating the stress levels at which different failure modes occur, and in correlating failure rate with stress levels. Such tests are somewhat expensive and time consuming, and are not normally used as acceptance tests.

c. Multivariate life tests, which subject the item to a combination of different stresses with varying levels of intensity. These tests are usually applied as product qualification or design approval tests, as well as in basic research and development studies. Multivariate tests utilize sophisticated techniques of statistical experimental design, and require the use of somewhat complex statistical techniques, such as multiple regression analysis, and analysis of variance. Multivariate life tests are time consuming and usually require expensive test and data processing facilities.

Strength oriented tests are often used to evaluate part reliability when it becomes impractical to run the time-consuming life tests. However, such tests provide qualitative information and do not provide quantified part failure rate data. This type of testing provides an indication of the strength or ability of the part to withstand stresses resulting from quantifiable environmental or electrical influences. These tests are performed by increasing stress levels until failure occurs. Statistical analysis of the stress-to-failure data provides information that can be used to establish "safety margins" between the stresses likely to be encountered during operation and the probable strength of the part.

Degradation oriented testing provides a measure of failures likely to result from steady degradation of electrical or physical characteristics of the part. A degradation failure occurs when the characteristic changes sufficiently to cause circuit malfunction. Consequently, failure by degradation is a function not only of the part itself but of the characteristics of the circuit within which it is used. By means of a special series of tests, it is possible to determine the expected characteristics of a part, the probable variation of similar parts as they are produced, and the manner in which the characteristics can be expected to change with time. Thus, if the circuit in which the part is to be used is analyzed to determine the allowable part parameter tolerance, the prospective

parts can be selected in a manner that will minimize degradation failures. The circuit analysis required to establish part tolerance can be performed with reasonable economy. However, initial testing to define the degradation or parameter drift rate characteristics of part can be time consuming and expensive.

3.3 Improving Part Reliability by Derating

The discussion of the preceeding paragraphs considered the part itself in improving reliability, in that the procedures described are directed toward assuring that parts selected are inherently reliable and capable of withstanding the stresses to which they will be submitted. Additional improvements in part reliability can be realized, however, by applying the techniques of derating which consider the functional design of the equipment in which the parts are to be used.

Derating, i.e., operating a part at less severe stresses than those for which it is rated, is effective because the life of most parts tends to increase as the applied stress levels are decreased below the rated value. In general, derating involves either altering a design to reduce the stresses applied to an individual part, or using a part capable of withstanding higher stresses than those present.

Derating procedures vary with different types of parts and their application. Resistors and capacitors, for example, are derated by decreasing the ratio of operating electrical stress to rated electrical stress. As an example, a resistor rated at 4 watts will be derated by a ratio of 0.5 when used in a 2 watt application. Electron tubes and semiconductors, are also derated by keeping the power dissipation below the rated level. Other parts, notably capacitors, are derated by maintaining the applied voltage at a lower value than the voltage for which the part is rated.

One procedure for derating of electronic parts involves the use of derating curves which usually relate derating levels to some critical environmental or physical factor. Such curves typically are included with the specifications for the part in question. A typical derating curve is illustrated in Figure 11-2. This curve indicates the relationship between operating power derating ratios and maximum allowable ambient temperature for carbon composition resistors. Conversely, the derating curve also indicates the minimum amount of derating necessary before a part can be operated at a given ambient temperature. This curve only indicates the amount of derating necessary to preclude degrading the reliability of the part. This does not quantify the reliability improvement that will be achieved by additional derating.

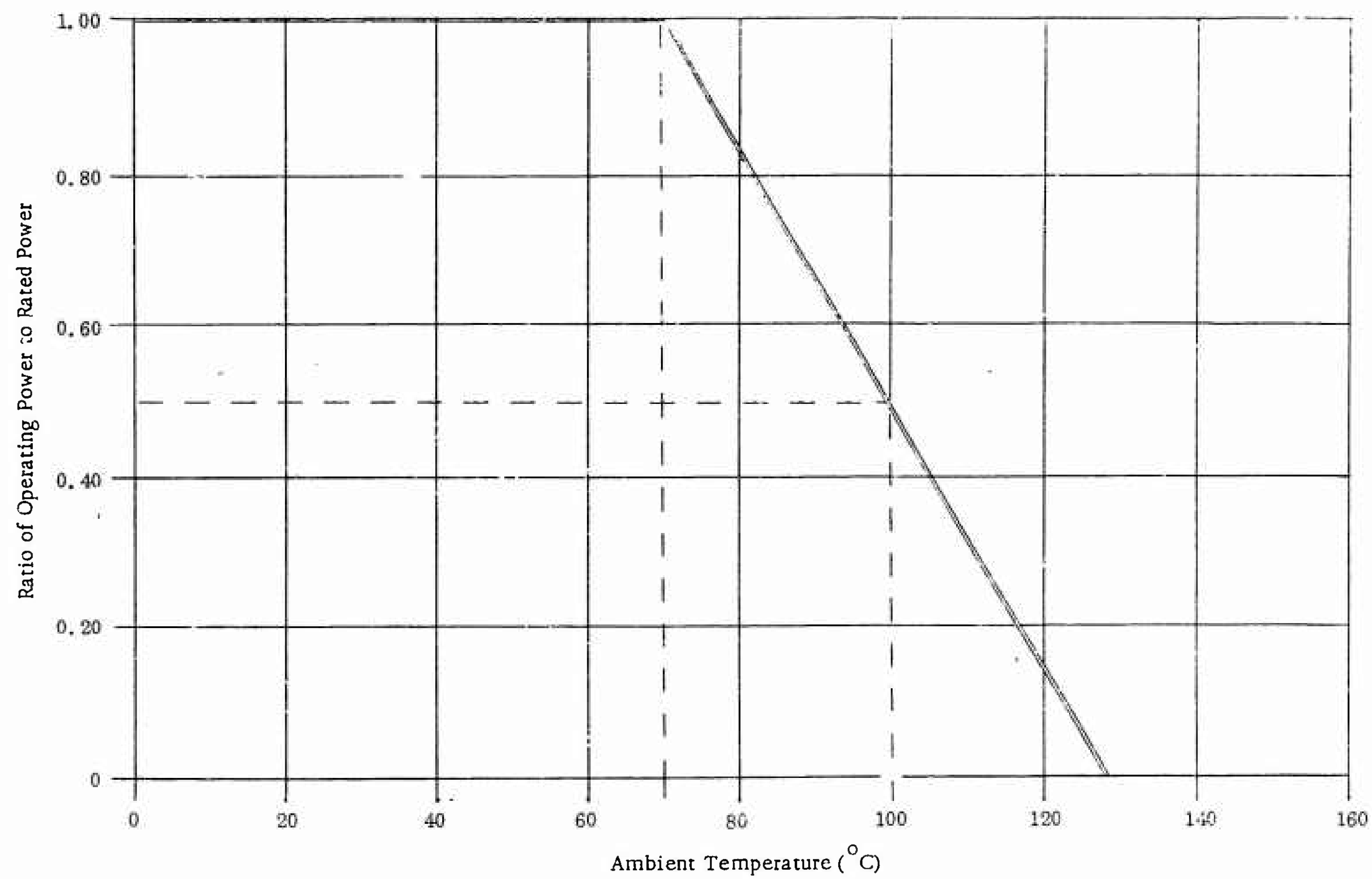


Figure 11-2. Derating Curve From Military Specification MIL-R-11. (Fixed Carbon Composition Resistors.)

More precise evaluation of reliability improvement resulting from derating can be obtained from failure rate vs. applied stress curves as used in reliability prediction. For example, the failure rate vs. applied stress curves used in reliability prediction relates stress ratio and ambient temperature levels to resulting failure rate. Thus the results of derating to any given level can be quantified in terms of reliability improvement. The failure rate curves in Volume II of this notebook are typical of such curves.

One disadvantage of derating is that any improvement in reliability is usually accompanied by an unavoidable increase in either the total number or physical size of parts used. Thus, it it apparent that engineering decisions concerning part derating will involve certain trade-off analyses to weigh the improvement in reliability against the associated increases in weight, volume, and possible cost.

For example, derating of composition resistors usually involves an increase in the physical size of the resistor. Therefore, trade-off decisions may be required to weigh relative reliability improvement against increasing size.

A typical derating trade-off curve representative of such relationships is presented in Figure 11-3. This figure indicates that use of a resistor of greater than 1/2 watt rating in a 1/10-watt application will probably not be justified, especially if volume is a critical factor.

Trade-off between reliability and weight, volume or some other variable often requires quantification of the failure rate reduction per unit change in the end item weight or volume. One such measure is the derating figure of merit (dfm) which simultaneously relates changes in failure rate, with associated changes in weight, and volume. Such a dfm is mathematically expressed as:

$$\text{dfm} = \frac{\Delta\lambda}{W_i \Delta V + \Delta W V_i + \Delta W \Delta V}$$

where

$\Delta\lambda$ is the failure rate reduction due to an incremental step in derating.

ΔW is the change in weight due to the use of a higher rated part.

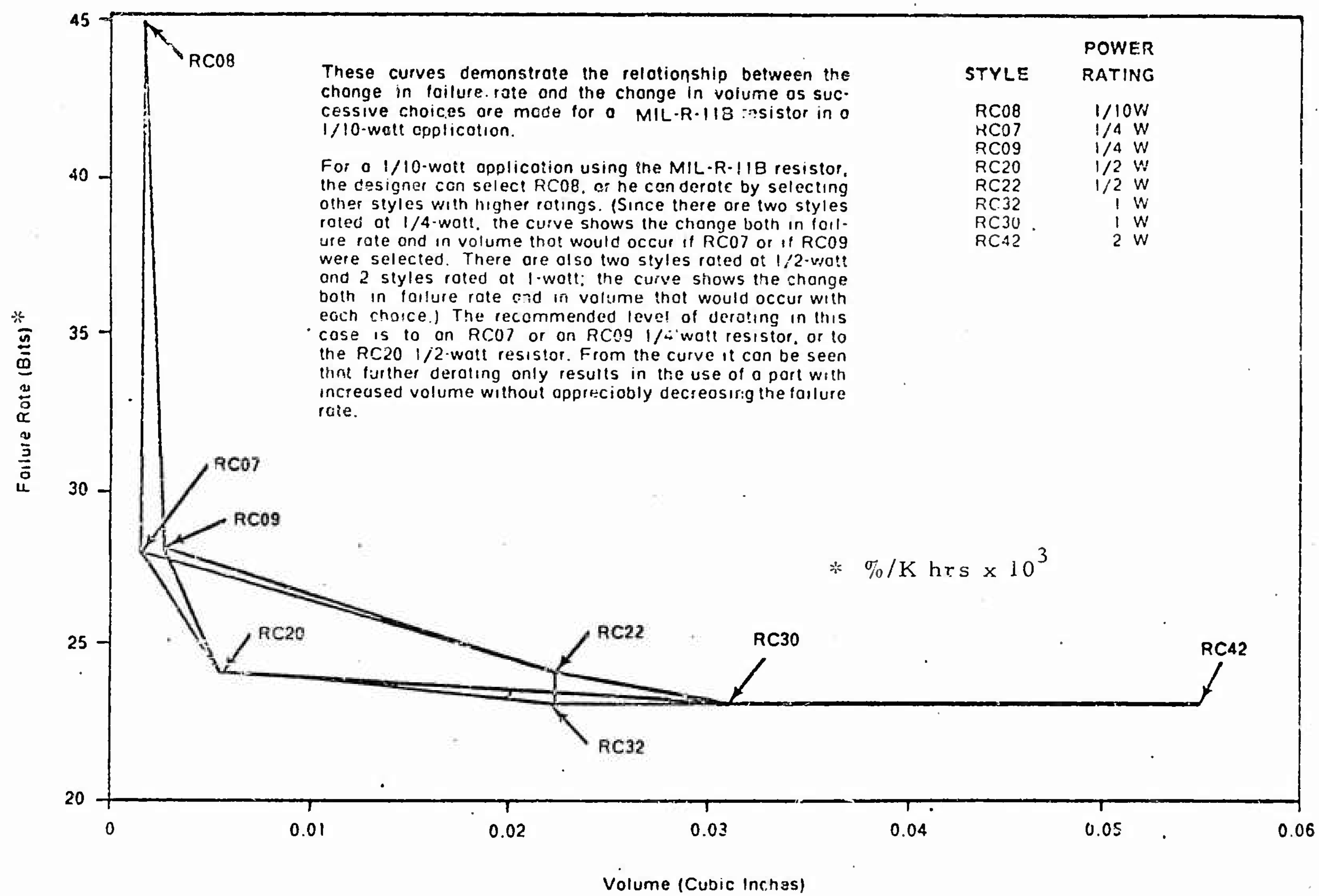


Figure 11-3. Typical Derating Trade-Off Curve for Resistor MIL-R-11B. (Extracted from Bureau of Ships Reliability Design Handbook NAVSHIPS 94501.)

ΔV is the change in volume due to the use of a higher rated part.

W_i is the initial total weight of all parts that are considered for derating.

V_i is the initial total volume of all parts that are considered for derating.

It may be necessary in many designs to obtain maximum reliability within specified limits of weight and volume. In such instances all parts to be derated must be evaluated from an overall design point of view to select the best combination of parts to be derated and the level to which each should be derated. The dfm provides means for making a comparison of the changes in failure rate, weight, and volume of many parts, and thus defines the combination of parts to be derated and the level to which each part should be derated to provide the greatest improvement in reliability of an equipment with a minimum increase in the physical dimensions of the equipment.

4. ENVIRONMENTAL STRESS CONSIDERATIONS IN RELIABILITY IMPROVEMENT

Up to this point, this chapter has been concerned with methods for improving reliability by assuring that parts selected for use in equipments are inherently reliable, and by assuring that stresses created by the equipment do not seriously degrade the potential reliability of the parts. Further improvement in equipment reliability can be realized by recognizing and counteracting certain degrading stresses created by the environment in which the equipment will be operated. In fact, ignoring such factors in system design can result in a complete compromise of the potential reliability level.

The importance of considering environmental factors in system design has been recognized for many years, and concerted efforts to solve the problems were initiated long before "reliability engineering" was recognized as a separate discipline. This effort has resulted in the development of standardized procedures such as those established in MIL-STD-810(USAF) for testing the ability of an item to withstand the deleterious effects of environments peculiar to military operations. Such testing requirements are now imposed as part of the quality assurance and acceptance testing provisions of virtually all system and end item specifications.

An important aspect in reliability improvement is the identification and accurate description of the environments to which the equipment will be subjected, consideration of the manner in which the various environmental

stresses effect equipment reliability, and development of appropriate objectives for the equipment engineering activities. This involves considering a variety of atmospheric, physical force, and radiation factors that characterize the use environment.

4.1 Atmospheric Stresses That Degrade Reliability

The following discussion highlights some of the characteristics of the environmental atmosphere, which can seriously degrade equipment reliability.

a. Temperature Extremes. The range of ambient temperatures expected in ground operations is -65° to $+125^{\circ}$F. Even greater extremes are encountered in world-wide operation and storage. For example, surface transportation and storage temperature as low as -80° F can be expected, while temperatures in densely packed electronic equipment may reach 400° F in the vicinity of tubes. These temperatures have relatively little effect on most metals and ceramics, but can greatly effect the physical properties of lubricants, plastics and other organic materials.

   In an equipment, high temperature conditions may cause the permanent set of packings and gaskets. Binding of parts may also result in items of complex construction due to differential expansion of dissimilar metals. Rubber, plastic, and plywood may tend to discolor, crack, bulge, check or craze. Closure and sealing strips may partially melt and adhere to contacting parts. At the opposite extreme, a few of the difficulties associated with low temperatures are differential contraction of metal parts, loss of resiliency of packings and congealing of lubricants.

b. Thermal Shock. Additional damage can result from a sudden change in temperature, even though the extremes in temperature mentioned above may not be reached. Such thermal shock can be encountered during rapid altitude changes during aerospace service, or while an equipment is being transported from one temperature extreme to another during ground service. A typical temperature shock test would involve temperature changes from -40° F to $+185^{\circ}$ F within a time span of 5 minutes.

   Effects of thermal shock include cracking and delamination of finishes, cracking and crazing of embedding and encapsulating compounds, opening of thermal seals and case seams, leakage

of filling materials, and changes in electrical characteristics due to mechanical displacement or rupture of conductors or of insulating materials.

c. Low Pressure. Damaging effects of low pressure include leakage of gases or fluids from gasket sealed enclosures and rupture of presurized containers. Under low pressure conditions low density material tend to sublime and many materials change their physical and chemical properties.

In addition, erratic operation or malfunction of equipment may result from arcing or corona, and greatly decreased efficiency of convection and conduction as heat transfer mechanisms under low pressure conditions increase the high and low temperature problems.

In general, the low-pressure extreme is in the order of 3.44 inches of mercury (equivalent to 50,000 feet altitude). However, in counteracting the effects of low pressure, the design engineer may often be concerned with pressures such as those experienced at altitudes as high as 100,000 feet and even higher, with the limit being the nearly total vacuum of space.

d. Humidity. High humidity, especially when combined with high temperature is another atmospheric problem encountered by the reliability engineers. Corrosion is the most common effect of humidity. However, hygroscopic materials also are sensitive to moisture and deteriorate rapidly under humid conditions. Absorption of moisture by many materials results in swelling, which destroys their functional utility and causes loss of physical strength and changes in other important mechanical properties. Insulating materials which absorb moisture may suffer degradation of their electrical properties.

e. Atmospheric Contamination. Salt, sand and dust contamination in the atmosphere are significant problems in land-based equipment. For example, no metal is immune to the effects of salt air. Salt in the atmosphere can significantly accelerate corrosion. Furthermore, galvanic corrosion can be a serious problem when any two metals are in contact in the presence of salt and moisture. For this reason, protective devices such as zinc or cadmium coatings often fail in salt air because they form galvanic couples with the base metal.

On deserts, beaches, volcano ash deposits, or plowed fields, dust and sand are a hazard to mechanical reliability. Airborne dust and fine sand can enter seemingly impenetrable locations,

and accumulate to cause accelerated wear in bearings of shafts and motors. In addition, dust with a static charge accumulates at points of high potential, increasing the risk of arc-over. If the dust is hygroscopic or if the humidity is high, the water-dust mixture forms an ionized path for arc-over.

f. <u>Breathing.</u> Alternate day heating and night cooling, or alternate increasing and decreasing of atmospheric pressure, can cause an intake-exhaust cycle known as breathing. This can result in an acceleration of the effects of humidity and atmospheric contamination and, therefore, is an important consideration in reliability improvement.

4.2 Physical Stresses That Degrade Reliability

In addition to the characteristics of the atmosphere, the operating environment also includes certain physical stresses which must be considered in any reliability improvement program. The more significant of these are the shock and vibration forces encountered during transportation and handling as well as during operation.

The first problem in reducing damage due to shock and vibration is that of determining the nature of the forces that will be encountered. This involves a careful study of the use environment and can involve prediction of a wide range of complex characteristics such as amplitude and duration of shock, or frequency and amplitude of vibration.

In addition to defining the physical forces, an even more difficult problem is encountered in determining their effect on the equipment, and in developing means for counteracting these forces. This can involve extensive engineering analyses to assess moments of inertia, resonant frequencies, and other characteristics of a proposed design, predicting how the items will react to the external forces, and devising methods for preventing damage. Such mechanical engineering activities are not defined as part of reliability improvement, but are essential to the total reliability of the system.

4.3 Radiation Phenomena That Degrade Reliability

Electromagnetic and nuclear radiation are some additional factors that must be considered in improving system reliability in the use environment. Even though the effect of the two types of radiation is quite different, both can cause degradation in the operational effectiveness of a system and, therefore, must be considered as factors in reliability improvement.

a. Electromagnetic Radiation. Electromagnetic radiation does not cause physical damage and, therefore, is not a factor in the "hardware" reliability. However, interference due to both natural and man-made radiation sources often degrades the operational effectiveness of electronic systems to the extent that serious "operational" reliability problems are experienced. Therefore, the identification of possible sources and characteristics of unwanted electromagnetic radiation and counteracting the adverse effects of such radiation is an important part of the overall reliability improvement activity.

Interference can be caused by any unwanted signal or random noise originating from a variety of terrestrial and extra-terrestrial sources. For example, electromagnetic noise is generated by natural sources such as lightning and aurora activity, and interference from solar and celestial sources is not uncommon. In addition, automobile ignition, electrical machinery and high tension transmission lines are typical sources of unavoidable man-made interference. Also, noise is generated within the disturbed equipment itself. This includes random "shot effect" noise from electron tubes, resistor noise, motor noise and component microphonics.

Methods for reducing the effect of electromagnetic noise interference are as varied as are the sources and characteristics of the noise. Therefore, interference reduction will involve many different engineering activities, ranging from development of input filters and shielding devices to development of superior piece parts and basic material. (See Reference 11 at the end of this section.)

b. Nuclear Radiation. Unlike electromagnetic radiation, nuclear radiation can cause physical damage to equipment items and material and, therefore, is a direct consideration of the reliability improvement program. Radiation can cause temporary or permanent damage to many types of electronic parts, primarily by affecting organic materials used in insulation and dielectrics. Certain inorganic compounds are also affected where alteration of the atomic or molecular configuration will degrade performance. Some typical effects of nuclear radiation on electronic devices are:

- Temporary or permanent alteration of semiconductor device characteristics due to production of extra carriers by gamma radiation, and alteration of the atomic structure of the semiconductor material by fast neutron bombardment.

- Alteration of the characteristics of resistance elements of various type of resistors. Significant damage due to high energy radiation can occur in carbon composition, film and wirewound resistors. This damage is primarily due to deterioration of organic insulating or binding material.

- Temporary or permanent damage to transformers due to damage to organic insulating material, ionization of gasses which reduce insulation resistances and increase arc-over damage, and changes in magnetic properties of core material.

4.4 Reliability Problems in the Space Environment

Various factors affect the operation and reliability of electronic equipment in space. Much is still to be learned. However, some phenomena such as low pressure, temperature extremes, ionization, and Doppler shifts, are known to create serious reliability and operational problems.

a. Electric Breakdown. A major effect of the lack of gas pressure in space is the reduction in breakdown voltage. Breakdown voltage is also reduced in an ionized atmosphere. It is conceivable that the gaseous regions surrounding the moon and planets may both be ionized and have reduced pressure, and that electric breakdown in these regions and in space will be a problem.

b. Ionization. Ionization can refract, reflect, attenuate, and scatter radio waves and, therefore, can affect operational reliability. The effect, however, decreases sharply with increase in frequency. The possibilities of ionospheres existing around the heavenly bodies, and of generation of ion clouds by cosmic explosions and meteor bursts, would indicate problems in the lower frequency range. Above 1, 000 mc, ionization effect should be negligible.

c. Doppler Shifts. From a lunar orbiting vehicle to earth, the Doppler shift at 1, 000 mc can be as high as 100 kc, and greater for higher frequencies. Thus band-pass problems are created that would not be a consideration in ground or air-based environments.

d. Temperature. An inert body in space eventually reaches a state of equilibrium with its environment. A body as close to the sun as Venus will have a temperature of 131° F. At a distance equal

to that of the Earth from the sun, temperature will be 43° F. Temperature will continue to decrease, with increase in distance from the sun, to the low of -454° F in interstellar space.

Reflecting bodies, such as the Earth, can contribute to the energy absorbed by bodies in space. The reflecting side of the Earth will produce 15 to 30 percent of the total energy absorbed by a body at an altitude of 1, 000 miles.

Mechanical design to dissipate to space (the ultimate heat sink) the absorbed energy plus that body heat given off by the equipment crew is a continuing problem. In addition, higher temperatures contribute to the general noise level.

e. Other Factors. Other factors that may affect performance of electronic equipment in space are meteors and meteorites; multipath effects in which reflections from space dust clouds cause interference patterns in the signal; the time required for transmission over large space distances; and error in orbiting paths and computations.

5. COUNTERACTING ENVIRONMENTAL STRESSES

In view of the diversity of environmental stresses that can degrade reliability in the operating environment, it is apparent that many different engineering disciplines will be required to develop protective or counteracting design techniques that will result in improved reliability. In many cases, these activities will not involve specific activities identifiable as "reliability engineering." However, the total engineering effort in reducing the effect of adverse environmental stresses is directed toward the single objective -- improvement of operational reliability.

Discussion of the various techniques for counteracting environmental stresses is outside the scope of this notebook. However, Table XI-1 will indicate some typical techniques used in counteracting the effects of various types of environmental stresses.

6. REDUNDANCY

The most effective means of improving system reliability, beyond the level achievable through selection of reliable parts and protecting these parts from operational and environmental stresses, is through the application of redundancy techniques.

Table XI-1 Reliability Improvement Techniques Vs. Environmental Stress

Type of Stress	Effects	Reliability Improvement Techniques
High Temperature	Mechanical deformation and deterioration, increased chemical activity (corrosion, etc.)	Heat dissipation devices, cooling systems, thermal insulation, heat-withstanding materials.
Low Temperature	Deformation from contracting material, congealing liquids, loss of resiliency.	Heating devices, thermal insulation, cold-withstanding materials.
Thermal Shock	Crazing, delamination, ruptured seals.	Combination of techniques for high and low temperatures.
Low Pressure	Leakage of gasses, ruptured containers, sublimation, arcing, poor heat transfer.	Increased mechanical strength of containers, pressurization, alternate liquids (low volatility) improved insulation, improved heat transfer methods.
Humidity	Corrosion of metals, deterioration of organic materials, degraded insulation.	Hermetic sealing, moisture-resistant material, dehumidifiers, protective coatings.
Salt Air	Corrosion, galvanic action, decreased insulation resistance.	non-metal protective covers, reduced use of dissimilar metals in contact, hermetic sealing, dehumidifiers.

Table XI-1 (Cont'd)

Type of Stress	Effects	Reliability Improvement Techniques
Sand and Dust	Abrasion, contaminates insulation, corona paths.	Air-filtering, hermetic sealing.
Breathing	Increased humidity, salt air, and sand and dust effects.	Hermetic seals, positive pressurization, controlled temperature and pressure.
Shock	Physical damage.	Strengthened members, reduced inertia and moments, shock absorbing mounts.
Vibration	Metal fatigue, physical damage.	Stiffening, control of resonance, reduced freedom of movement.
Electromagnetic Radiation	Damaged materials, altered electrical characteristics.	Shielding, material selection, part type selection.

In reliability engineering, redundancy can be defined as the existence of more than one means for accomplishing a given function within an equipment or system. Essentially, a system or equipment has redundant functions if, after the failure of one or more of its elements, it continues to perform at a satisfactory level. This implies that an alternate method is available to perform the function.

Redundancy can permit an equipment to exhibit better reliability than its elements, and the effective reliability of a system to be higher than that of any of its equipments. However, the degree of improvement is dependent on the type of redundancy employed and the characteristic of the particular system or equipment. Some of these considerations are discussed below, together with an introduction to certain mathematical aspects in the evaluation of the reliability of redundant configurations. Also, certain trade-off considerations concerning cost, weight and space penalty are introduced.

6.1 Classes of Redundancy

There are two general classes of system or equipment redundancy: (1) Natural Redundancy, where a system's fragmented structure, and variety of operating modes permits some acceptable level of system performance even though some failure or degradation has occurred, and (2) Design Redundancy, where duplicate or alternate elements are specifically designed-in to perform duplicate functions in the event of a failure, and thus allow continued performance without degrading equipment performance. These two general classes are discussed more fully in the following paragraphs.

a. Natural Redundancy. Operational characteristics of complex systems often provide alternate methods for performing given types of operational functions. Thus, many systems have a large number of useful states which permit successful, although degraded performance even though certain elements of the system fail.

One example of natural redundancy is a radar system that utilizes a PPI and a B scope, each having a specific operational function. For maximum performance, both types of scopes must be in an upstate. However, the two types of scopes have certain features in common such that if one scope should fail the other could compensate for the failed scope and the system would still be operating, but at a degraded level.

Many possible areas of natural redundancy exist in most systems. Therefore, it is often possible to achieve a significant improvement over the basic reliability of the system by simply

recognizing and utilizing the alternate functions that exist. This potential for reliability improvement should be fully explored and exploited before resorting to the more expensive application of design redundancy. The full potential for reliability improvement through the use of natural redundancy, however, can only be realized by completely enumerating all possible system operating states and their associated functions. Therefore, one area of reliability improvement is that of describing the performance characteristics of the various system states and evaluating the true system reliability with respect to all potential alternate functions. This effort requires analysis to determine the following:

- Definitions of all performance requirements of the system.

- Complete functional configuration of the system considering all modes of operation.

- Degradation analysis of the system to determine allowable levels of degradation, and to define the true conditions constituting a failure.

- Designation of the appropriate reliability model and mean life formulae that consider the results of the degradation analysis.

- Designation of the failure and repair rates of all units that comprise the system and using them as input data to solve the model and mean life formulae.

b. Design Redundancy. Design redundancy includes all system or equipment configurations in which redundant elements have been included specifically to improve reliability. There are several types of design redundancy which can be described according to (a) the operational state of the redundant elements while the system is in operation, (b) circuit configuration, and (c) the existence or nonexistence of decision and switching (DS) devices. Several basic redundant configurations are illustrated in Figure 11-4. The effectiveness of each of these configurations in improving reliability is dependent on the manner in which the circuit fails, as well as the circuit configuration. Some general considerations in the application of the various redundant element configurations are:

- Parallel Redundancy. Parallel redundancy (Diagram A of Figure 11-4) is used when the dominant mode of element failure is open circuits. If one of the two elements fail in an open condition, (was removed from the configuration) the

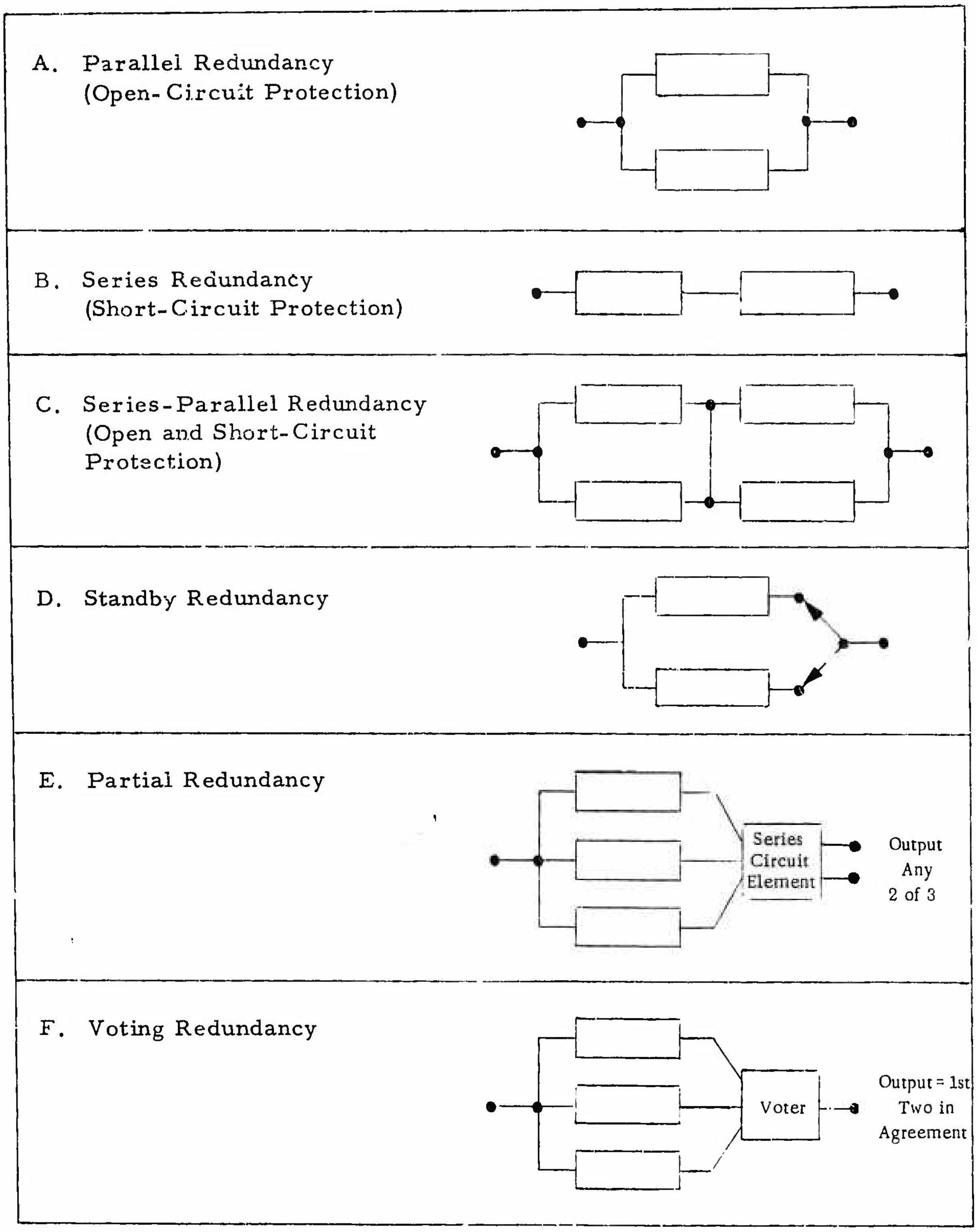


Figure 11-4. Redundant Element Configurations

other could still perform the required function. This arrangement does not provide protection against short circuits and, actually, increases the failure probability due to short circuits.

- Series Redundancy. Series redundancy (Diagram B of Figure 11-4) is an arrangement which provides protection in the event of "short circuit" failure because one element could perform the required function even though the other element was short-circuited. This arrangement, however, is vulnerable to open circuit failures.

- Series-Parallel Redundancy. A series-parallel redundant configuration (Diagram C of Figure 11-4), and variations of this basic configuration, provide increased reliability under conditions in which the basic parallel or series configurations are not effective. For example, this configuration would be equally effective in the event of either open - or short-circuit failures.

- Standby Redundancy. In many instances it is impractical, from an engineering viewpoint, to use redundant configurations such as those discussed above in which all redundant elements are permanently connected and operational at all times. In such cases, standby redundancy (Diagram D of Figure 11-4) can often provide a solution to the engineering problem. In these configurations, an element is held in "standby" and switched in to assume the circuit function in the event of failure of the primary element.

  The spare element can be either on (active) all the time or off (inactive) when the primary element is performing its function. These two types of redundancy include switching elements that must be considered in evaluating the effective reliability of the overall configuration.

- Partial Redundancy. Partial redundancy is a special case of redundancy wherein several parallel outputs are channeled through a single series device such as a decision-making circuit which provides the required function as long as a predetermined number of the parallel outputs are in agreement. The reliability of the series element is a critical factor in the effectiveness of this configuration. An example of partial redundancy is shown in Diagram E of Figure 11-4.

- Voting Redundancy. Another special type of redundancy includes means whereby the outputs of three or more operating redundant units are compared, and any one output that agrees with the majority of outputs is selected. This configuration, referred to as voting redundancy, is illustrated in Diagram F of Figure 11-4.

6.2 Evaluation of Redundant Configurations

One of the major reliability engineering activities during system design is the evaluation of redundant configurations to assess the achieved level of reliability improvement. Such evaluations not only provide a quantitative measure of reliability improvement, but also provide comparative data essential to many design trade-off studies. In general, evaluation of a redundant system configuration involves complex mathematical models which are unique to the specific system under consideration. However, any such model is composed of elements that can be defined in terms of elementary redundancy configurations, which are used as "building blocks" in developing the overall system model.

Redundant configurations are usually evaluated in terms of the probability of survival (or probability of failure) of individual elements of the system. This approach permits the application of basic rules of probability in developing a mathematical model of system reliability. In certain cases system reliability is evaluated in terms of MTBF or similar parameters. In general, however, techniques for performing evaluations such as this involve the combination of failure distribution functions and are beyond the scope of this notebook. Some of the more elementary redundant configurations, which can be evaluated in terms of MTBF without regard for failure distribution are discussed here for illustration purposes. Most of the discussion, however, is concerned with the more conversational probabilistic approach.

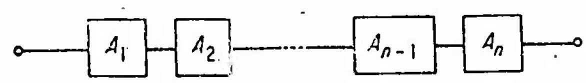
Procedures for developing models suitable for evaluating some of the more common elementary configurations are discussed below. These discussions are based on the following assumptions:

- The units under consideration are composed of independent elements whose operation can be described in discrete terms of "success" or "failure".

- All elements are continuously energized and switching devices are either unnecessary or are effectively failure-free.

- Failure of any type has no adverse effects on the operation of the surviving paths - e.g., precautions such as use of a fuse has been taken to avoid unit failure through shorting if a parallel path shorts.

a. Basic Series System Reliability. The method for evaluation of a non-redundant series system is discussed first to establish the basis for the evaluation of redundant configurations. A non-redundant series system of n elements can be represented by the following diagram:



The reliability of this "n-element series system," under the basic assumptions of independent element failures and the necessity of successful operation of all elements for system success, is

$$R = p_1 \cdot p_2, \ldots, p_n \tag{1}$$

where $p_1, p_2, \ldots, p_n$ are the reliabilities (probability of survival) of elements $A_1, A_2, \ldots, A_n$, respectively.

If all elements are identical with reliability p,

$$R = p^n \tag{2}$$

The MTBF of the basic series unit can be determined by considering the system failure rate to be the sum of the failure rates of the individual elements. The unit MTBF is the reciprocal of the system failure rate. Thus:

$$\lambda_{system} = \sum_{i=1}^{n} \lambda_i \tag{3}$$

where:

λ_{system} = the system failure rate.

λ_i = the failure rate of one element of the series unit.

n = the total number of series elements in the unit.

Taking the reciprocal:

$$MTBF = \frac{1}{\sum_{i=1}^{n} \lambda_i} \tag{4}$$

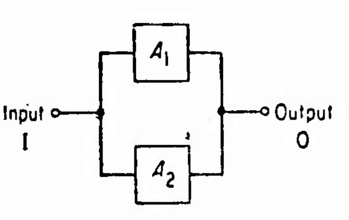
If all elements are equal, with failure rate λ, then:

$$MTBF = \frac{1}{n\lambda} = \frac{\theta}{n} \tag{5}$$

where:

$\theta = \frac{1}{\lambda}$ = the MTBF of one element of the unit.

b. Basic Parallel Redundant Configuration. Two elements in a parallel redundant configuration can be represented by a reliability block diagram as follows:



Blocks A_1 and A_2 represent independent elements, either of which can perform the required function. If the probability of element A_1 operating successfully over the specified time interval is p_1, and if p_2 is the corresponding probability for element A_2, the probability of success for the unit can be found by considering that the unit is successful if at least A_1 or A_2 is operable. Since both elements are energized, the events the operation of A_1 and A_2 are not mutually exclusive events - i.e., both A_1 and A_2 can occur. Therefore, the probability of success using the additive rule for non-mutually exclusive events is:

$$R = p_1 + p_2 - p_1 p_2. \tag{6}$$

An alternate derivation can be obtained by defining conditions of failure. The only way the unit can fail is through failure of both elements. Since the operation of A_1 and A_2 are assumed to be independent events, the probability that both elements fail is the product of their unreliabilities. If $\bar{R}$ is the "unreliability" or probability of failure of both elements, and $(1-p_1)$ and $(1-p_2)$ are the respective probabilities of independent failure of elements A_1 and A_2, then:

$$\bar{R} = (1-p_1)(1-p_2)$$

But since the probability of either a failure or a success is unity, $R + \bar{R} = 1$, and

$$R = 1-(1-p_1)(1-p_2) \tag{7}$$

Expressions (6) and (7) are equivalent, and either can be used for evaluating the reliability of two parallel redundant elements.

If the two elements are identical with reliability p, expression (6) and (7) become:

$$R = 2p-p^2, \text{ and}$$

$$R = 1-(1-p)^2$$

Example: If $p_1 = p_2 = 0.90$, by the additive rule of expression (6): $R = 0.90 + 0.90 - 0.81 = 0.99$.

Or by the multiplicative rule of expression (1):

$$R = 1-(1-.90)(1-.90) = 1-.01 = .99$$

c. Multiple Parallel Redundant Configuration. By extension of expression (7), the general expression for the reliability of a unit with m parallel elements is:

$$R = 1 - (1-p_1)(1-p_2)\ldots(1-p_m) \tag{8}$$

If all elements are identical with reliability p, then:

$$R = 1 - (1-p)^m. \tag{9}$$

The general expression for the MTBF of a unit with m identical parallel elements is:

$$MTBF = \frac{1}{\lambda}\sum_{i=m-k}^{m} \frac{1}{i} \tag{10}$$

or:

$$MTBF = \theta\sum_{i=m-k}^{m} \frac{1}{i} \tag{11}$$

where:

MTBF = the mean time between failure of the unit.

λ = the failure rate of any one of the elements.

θ = the mean life or MTBF of any one of the elements.

k = the maximum number of elements that can fail without failure of the unit.

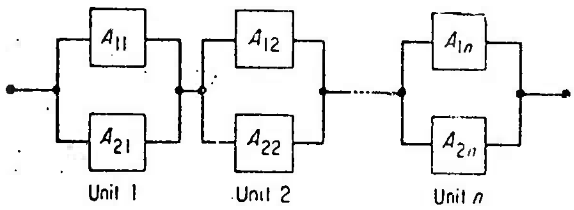
In the event that any one element can perform the total unit function, the unit will not fail until all m elements fail. In this case k = m-1, and expression (11) becomes:

$$MTBF = \theta\sum_{i=1}^{m} \frac{1}{i} = \theta\left(\frac{1}{1} + \frac{1}{2} + \ldots + \frac{1}{m}\right) \tag{12}$$

Applying expression (12) in the special case of two identical parallel elements, as discussed in paragraph b above, would yield:

$$\text{MTBF} = \theta\left(\frac{1}{1} + \frac{1}{2}\right) = \frac{3\theta}{2}$$

d. Series-Parallel Configurations. A series-parallel configuration, is a series of n basic parallel units. The reliability block diagram of such a configuration will have the form shown in the figure below.



This is the series-parallel redundant counterpart of an n-element non-redundant system. For each unit there are two possible paths for unit success. The reliability of one of the units therefore can be determined using expression (7) giving:

$$r_j = 1 - q_{1j}q_{2j}$$

where $q = 1-p$.

Assuming that unit failure probabilities are independent, the system reliability is the product of unit reliabilities. Applying expression (1):

$$R = (1-q_{11}q_{21})(1-q_{12}q_{22})\ldots(1-q_{1n}q_{2n}) \qquad (13)$$

If all elements are identical, with a reliability of p and an unreliability of q then:

$$R = (1-q^2)^n. \qquad (14)$$

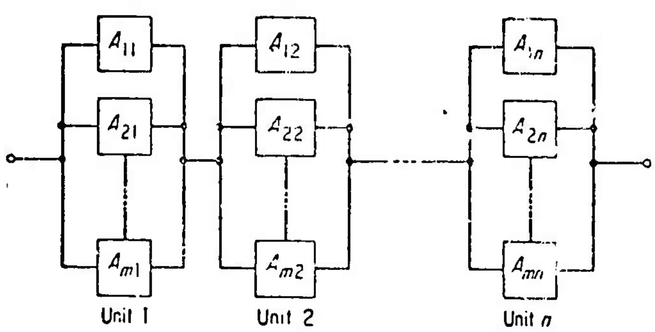
To illustrate the possible reliability advantages of redundancy for this simple model, assume a basic circuit of three identical elements, each with a reliability of 0.8 over the time period of interest. Without redundancy,

$$R = (0.8)^3 = 0.512.$$

When each element is duplicated by a series-parallel arrangement,

$$R = (1-q^2)^3 = (1-0.2^2)^3 = 0.885.$$

e. <u>General Series-Parallel Configurations</u>. In general, a series of multiple parallel elements rather than two parallel elements would have a configuration as shown in the figure below.



By extending the results given in expression (7),

$$R = \prod_{j=1}^{n} (1-q_{1j}\, q_{2j} \cdot \ldots \cdot q_{mj}), \tag{15}$$

where q_{ij} is the failure probability of the ith element in the jth unit.

If all elements in a unit are identical,

$$R = \prod_{j=1}^{n} (1 - q_j^{m}) \qquad (16)$$

Further, if all n units are identical, and made up of m parallel elements, each having probability of failure q, or reliability p,

$$R = (1-q^{m})^{n} = [1-(1-p)^{m}]^{n} \qquad (17)$$

An expression for the MTBF of a series-parallel configuration can be derived by combining expressions (5) and (11), such that:

$$\text{MTBF} = \frac{\theta}{n} \sum_{i=m-k}^{m} \frac{1}{i} \qquad (18)$$

where:

θ = the MTBF of any one element of the system (all elements are assumed to be identical).

m = the number of elements in any one parallel unit. (all parallel units are assumed to consist of an equal number of elements).

k = the maximum number of elements that can fail in any one parallel unit without causing system failure.

n = the number of units connected in series to make up the system. (All units are assumed to be identical).

6.3 General Expressions for Evaluation of Basic Redundant Configurations

Any configuration of redundant elements can be evaluated by developing models in the manner illustrated in paragraph 6.2. In general, the models for evaluating redundant configurations can become more complex than the simplified examples of paragraph 6.2, and will not be derived here. However, the reliability evaluation expressions for the general case of each of several basic configurations are presented in Figure 11-5. These expressions can be tailored to particular

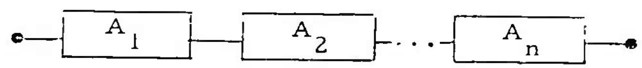
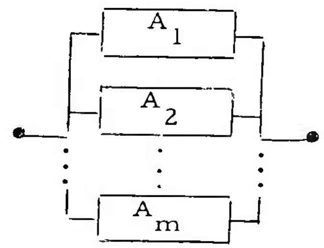
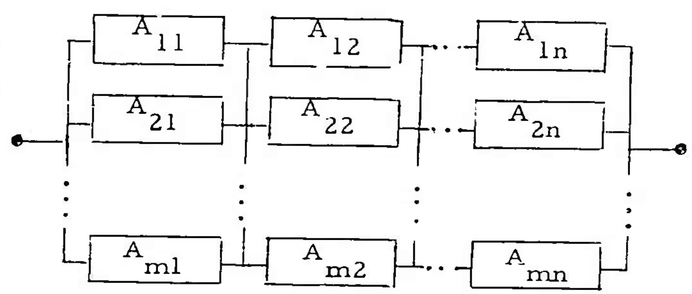
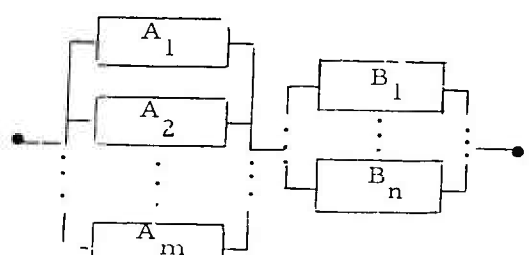
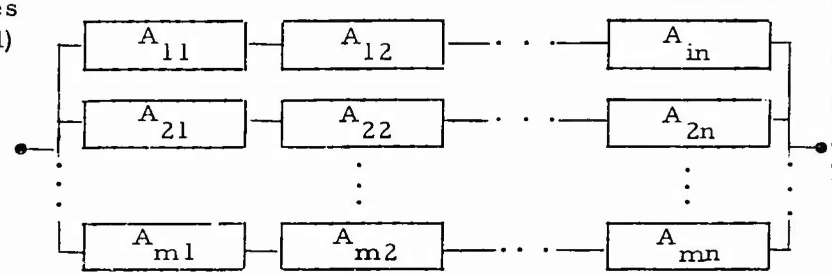
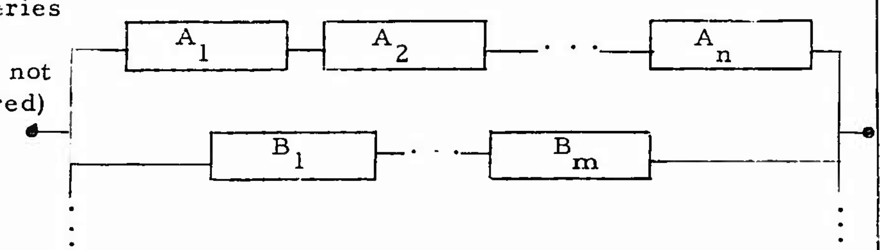
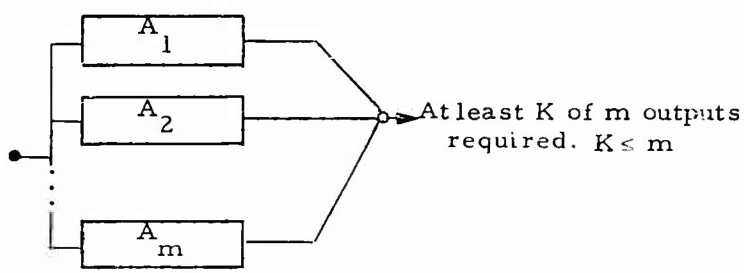
Configuration	Diagram	Expression	Remarks
(1) Series, Non-Redundant		$R = \prod_{j=1}^{n} p_j$ $R = p^n$ $MTBF = \frac{\theta}{n}$	p_j - Reliability of A_j All $p_j = p$
(2) Parallel		$R = 1 - \prod_{i=1}^{m} (1-p_i)$ $R = 1 - (1-p)^m$ $MTBF = \theta \sum_{i=m-k}^{m} \frac{1}{i}$	p_i - Reliability of A_i All $p_i = p$ k = max. allowable no. of failures
(3) Series-Parallel (Symmetrical)		$R = \prod_{j=1}^{n} (1 - q_{1j} q_{2j} \cdots q_{mj})$ $R = \prod_{j=1}^{n} (1 - q_j^{m})$ $R = (1 - q^m)^n$ $MTBF = \frac{\theta}{n} \sum_{i=m-k}^{m} \frac{1}{i}$	q_{ij} = fail probability of A_{ij} All $q_{ij} = q_j$ All $q_{ij} = q$ k max. allowable no. of failures
(4) Series-Parallel General (Symmetry not considered)		$r_A = 1 - \prod_{i=1}^{m} (1-p_i)$ $r_B = 1 - \prod_{j=1}^{n} (1-p_j)$ etc. $R = r_A \cdot r_B \cdots$	

Figure 11-5 Reliability of Basic Configurations

Configuration	Diagram	Expression	Remarks
(3) Parallel Series (Symmetrical)		$R = 1 - \prod_{i=1}^{m} (1 - p_{i1} p_{i2} \cdots p_{in})$	p_{ij} = reliability of A_{ij}
		$R = 1 - \prod_{i=1}^{m} (1 - p_i^{\,n})$	All $p_{ij} = p_i$
		$R = 1 - (1 - p^n)^m$	All $p_{ij} = p$
(6) Parallel Series General (Symmetry not Considered)		$r_A = \prod_{i=1}^{n} p_i$ $r_B = \prod_{j=1}^{m} p_j$ etc. $R = 1 - (1 - r_A)(1 - r_B) \ldots$	
(7) Partial Redundancy		$R = \sum_{x=K}^{m} \frac{m!}{x!(m-x)!} p^x (1-p)^{m-x}$	p = reliability of $A_1, A_2, \ldots, A_m$ (All equal)

Special Cases:

m	K	Reliability	
2	1	$R = 2p - p^2 = 1(1-p)^2$	
3	2	$R = 3p^2 - 2p^3$	
m	1	$R = 1 - (1-p)^m$	(see 2)
m	m	$R = p^m$	(see 1)

Figure 11-5 (Cont'd)

situations, and can be used in combination to define practical active redundancy configurations providing failure mode (open or short-circuit failures) is not a factor.

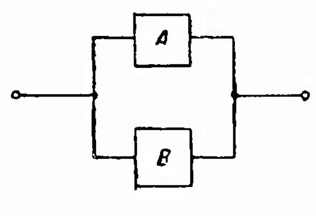
Symbols used in Figure 11-5 are defined as follows:

Symbol	Definition
R	Effective reliability (probability of survival) of the overall configuration.
r	Effective reliability of a defined portion of the overall configuration.
p	Reliability of a basic element.
q	Probability of element failure ($q = 1-p$).
MTBF	Mean Time Between Failures of the overall configuration.
θ	Mean Time Between Failures of any one of a number of identical elements in the configuration.

6.4 Consideration of Open-and Short-Circuit Failures

The previous redundant models were based on the assumption that individual element or path failure has no effect on the operation of surviving paths. However, this assumption is not always valid. Consider, for example, a simple parallel unit composed of two elements, A and B, each of which can fail by either open circuit failure or short-circuit failure. Short circuit failure of either of the two elements will "short out" the other element and, therefore, result in unit failure. Therefore, in many practical cases, evaluation of redundant configuration is complicated by the necessity of considering the type of failure. Methods for considering open and short-circuit failures in evaluating redundant configurations are reviewed below.

a. Reliability of Basic Parallel Configurations. For two elements in the active-parallel redundant configuration below,



the unit will fail if either of the following events occur:

(1) either A <u>or</u> B shorts, or

(2) both A <u>and</u> B open.

The respective probabilities of these two events are:

(1) P(A <u>or</u> B shorts) $= q_{sa} + q_{sb} - q_{sa}q_{sb}$

$$= 1 - (1-q_{sa})(1-q_{sb})$$

(2) P(A <u>and</u> B open) $= q_{oa}q_{ob}$

where q_{oi} is the probability that element i opens and q_{si} is the probability that element i shorts. Since events (1) and (2) are mutually exclusive, the probability of unit failure (P(F)) is the sum of the two event probabilities, or,

$$P(F) = P(A \text{ or } B \text{ Short}) + P(A \text{ and } B \text{ Open})$$

$$= 1 - (1-q_{sa})(1-q_{sb}) + q_{oa}q_{ob} \,.$$

R = 1-P(F), therefore,

$$R = (1-q_{sa})(1-q_{sb}) - q_{oa}q_{ob}$$

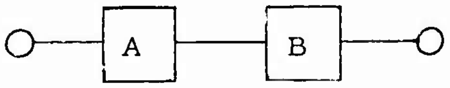
In general, if there are m parallel elements,

$$R = \prod_{i=1}^{m} (1-q_{si}) - \prod_{i=1}^{m} q_{oi} \,;$$

Further, if all m elements are identical:

$$R = (1-q_s)^m - q_o^m$$

b. <u>Reliability of Basic Series Redundant Configuration</u>. In general, a series redundant system will fail if one or more elements are open-circuited, or if all elements are short-circuited. For example, in the two-element series unit below:



the unit will fail if either of the following events occur:

(1) Both A and B short, or

(2) Either A or B opens.

(Note that this is opposite from the definition of failure for a two-element parallel unit.)

A derivation similar to that for the parallel case, but considering conditions of failure for the series redundant configuration gives:

$$R = (1-q_{oa})(1-q_{ob}) - q_{sa}q_{sb}$$

In general, if there are n series elements:

$$R = \prod_{i=1}^{n} (1-q_{oi}) - \prod_{i=1}^{n} q_{si}$$

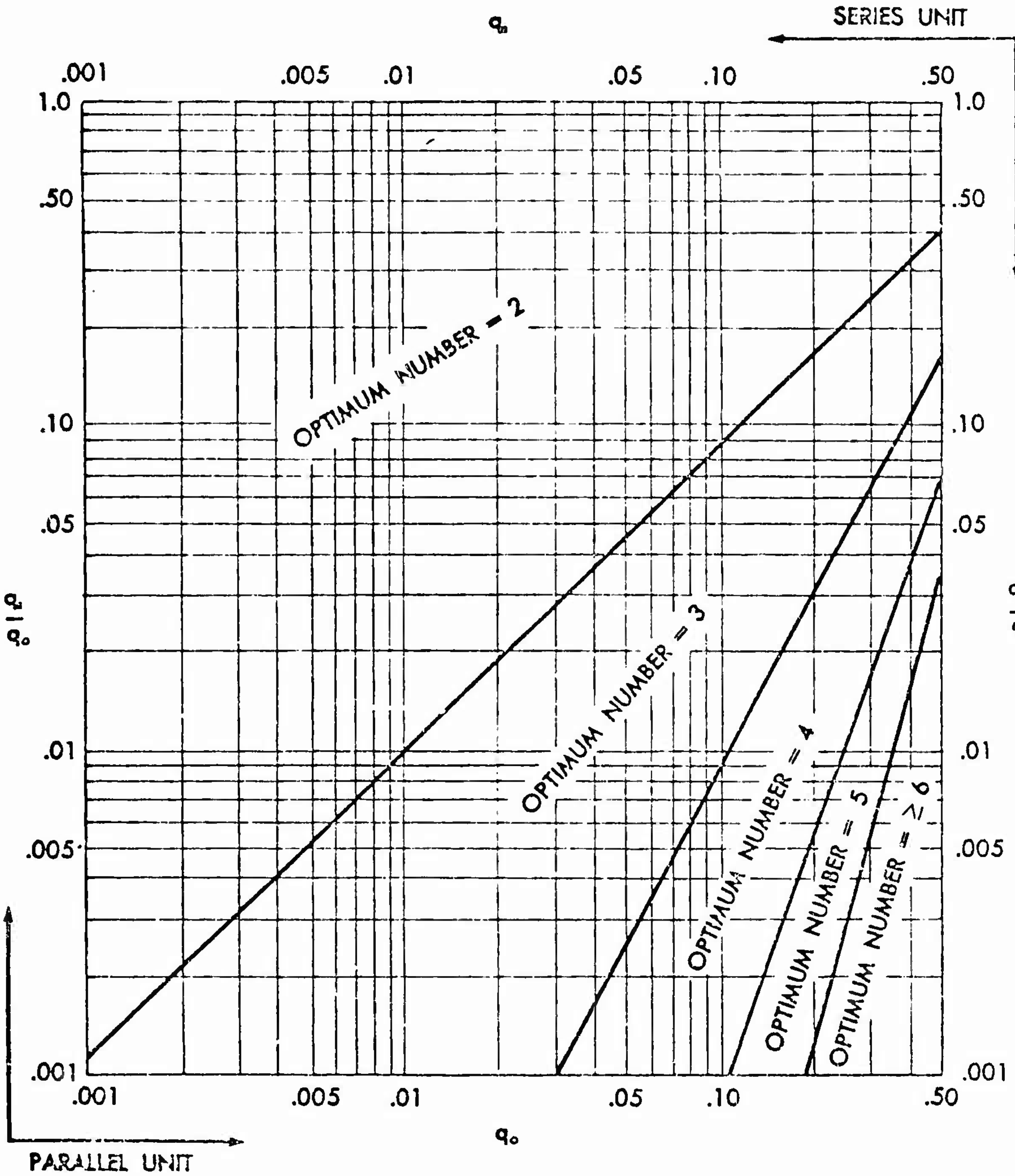
If all n elements are identical:

$$R = (1-q_o)^n - q_s^n$$

c. Optimum Number of Parallel or Series Elements. The expressions derived above for considering the effect of short- and open-circuit failure on the reliability of redundant elements indicate that an optimum number of parallel or series elements exists for various values of q_s and q_o. This is illustrated in Table XI-2, where the parallel expression, $R = (1-q_s)^m - q_o^m$, is solved for various values of q_s and m when q_o = 0.10.

Table XI-2. Values of R for q_o = 0.1

m	q_s = 0	q_s = 0.05	q_s = 0.10	q_s = 0.20
1	0.900	0.85	0.80	0.70
2	0.990	0.89	0.80	0.60
3	0.999	0.86	0.73	0.51



qs = probability of short-circuit failure of one element.

qo = probability of open-circuit failure of one element.

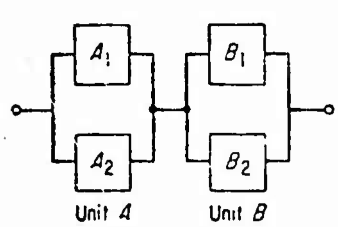
Figure 11-6. Optimum Number of Redundant Elements as a Function of Failure Mode Probabilities (Reproduced from NAVWEPS 00-65-502)

In the case where $q_s = 0$, unit reliability increases as the number of parallel elements is increased. In this case R would continue to increase as m is increased. In the case where $q_s = 0.05$, however, R increases as m is increased from 1 to 2, but decreases as m is further increased to 3. Therefore, m = 2 (i.e., two elements in parallel) will provide maximum reliability when $q_o = 0.1$ and $q_s = 0.05$, but 3 or more units in parallel would decrease the unit reliability. In the case where $q_s = 0.10$ parallel redundancy will not increase reliability, and when $q_s = 0.20$ (i.e., $q_s > q_o$), any parallel redundancy will actually decrease reliability. In the latter case, however, reliability could be increased by using series redundancy.

Figure 11-6 presents the general solution of the parallel and series reliability expressions for optimum numbers of redundant elements, while the relationships between q_s and q_o are varied. When q_o is greater than q_s, the curves are entered via the left-hand and bottom scales to determine the optimum number of parallel elements. When q_s is greater than q_o, the curves are entered via the top and right-hand scales to determine the optimum number of series elements. If $q_s = q_o$, then no increase in reliability is possible without resorting to more complex schemes such as series-parallel redundancy.

d. Series-Parallel and Parallel-Series Configurations. The reliability of series-parallel, and parallel-series configurations, when short-and open-circuit failure modes are considered and where all elements are equal, are determined by the following general expressions.

Series-Parallel

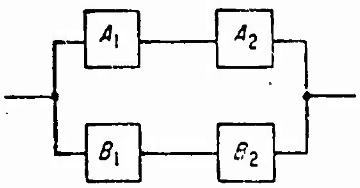


$$R_{sp} = [1-q_o^m]^n - [1-(1-q_s)^m]^n$$

m = number of parallel elements in each unit

n = number of units in series

Parallel-Series



$$R_{ps} = [1-q_s^n]^m - [1-(1-q_o)^n]^m$$

n = number series elements in each path

m = number of parallel paths

6.5 Redundancy Involving Switching

To this point, it has been assumed that devices for detecting element failure and switching-in redundant elements are either unnecessary or failure-free. However, many practical configurations involve switching elements which have some probability of failure.

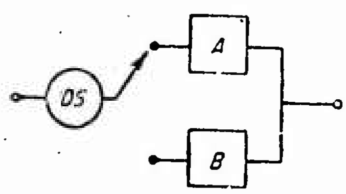
In general, a switching device is effectively an element in series with a redundant unit. However, the expressions for evaluating redundancies involving switching are complicated by the necessity for considering three general types of switching failures. These are:

> Dynamic failure - failure to switch when required
>
> Static failure - inadvertent or premature switching
>
> Contact failure - inability of the switch to maintain a good connection.

Dynamic switching failure always causes system failure; static failure causes system failure if the duplicate element has failed (assuming switching is only in one direction); and contact failure always causes system failure.

Time-dependent situations must be discussed before switching reliability can be treated fully; however, a simple example will prove fruitful in illustrating the effects of switching failure on redundancy applications.

Consider the following two-path parallel system which requires a decision and switching device and which remains latched to B once B is energized by the switch.



Three possible states that may lead to system success are:

State 1: A and B are successful (AB).

State 2: A succeeds, B fails ($A\bar{B}$).

State 3: A fails, B succeeds ($\bar{A}B$).

State 1 requires no contact failure (dynamic failure can occur only if A fails; and a static failure in this case does not result in system failure).

State 2 requires no contact failure and no static failure.

State 3 requires no contact failure and no dynamic failure (static failure cannot occur if A fails).

Let:

p_i = element reliability ($i = a, b$; $q_i = 1 - p_i$);

p_d = conditional dynamic reliability (switching when required);

p_t = conditional static reliability (no switching when not required);

p_c = contact reliability.

Consideration of each state will provide an expression for probability of success as follows:

$$R = \underbrace{p_a p_b p_c}_{\text{State 1}} + \underbrace{p_a q_b p_c p_t}_{\text{State 2}} + \underbrace{q_a p_b p_c p_d}_{\text{State 3}}$$

$$= p_c [p_a p_b + p_a q_b p_t + q_a p_b p_d] .$$

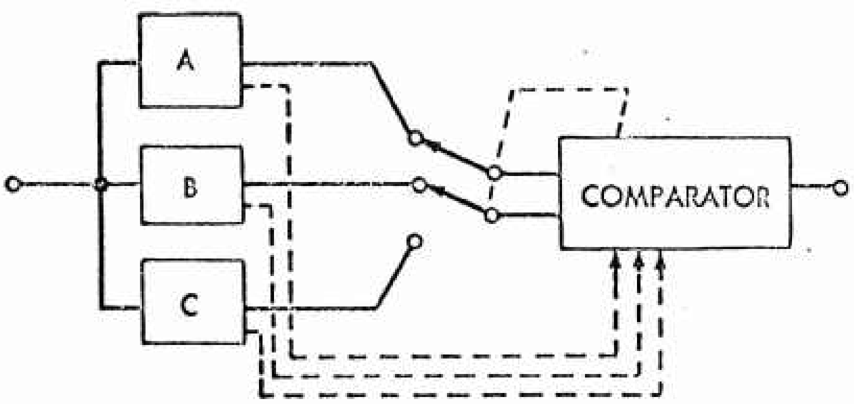
For simplicity, assume that $p_a = p_b = p$; $p_d = p_t = p'$; then,

$$R = p_c [p^2 + 2pqp'] .$$

For failure-free switching ($p_c = p' = 1.0$), $R = p^2 + 2pq$. This is greater than nonredundant reliability, p, and the redundancy application therefore increases reliability. However, if p_c and p' are less than 1.0, the relationships between p, p_c, and p' become important for determining if redundancy is beneficial and at what level it should be introduced.

6.6 Voting Redundancy

The following figure shows three elements, A, B, and C, and the associated switching and comparator circuit which make up a typical voting redundant system.



(From NAVWEPS 00-65-502)

Three-Element Voting Redundancy

The circuit function will always be performed by an element whose output agrees with the output of at least one of the other elements. At least two good elements are required for successful operation of the circuit. Two switches are provided so that a comparison of any two outputs of the three elements can be made. The comparator circuit operates the switches so that a position is located where the outputs again agree after one element fails.

If comparison and switching are failure-free, the system will be successful as long as two or three elements are successful. In this case the reliability expression becomes:

$$R = p_a p_b + p_a p_c + p_b p_c - 2p_a p_b p_c$$

In a practical case, however, failure-free switching cannot be assumed, and conditional probabilities of switching operation must be considered. Consider the probability of the comparator and switches failing in such a manner that the switches remain in their original positions. If this probability is q_s, then:

$$R = p_a p_b + (p_a p_c + p_b p_c - 2p_a p_b p_c)(1 - q_s)$$

The complete problems involve the consideration of each of the various possible modes of switching failure together with the necessity for specific switching requirements in the event of each element failure. This is, obviously a complex problem and is beyond the scope of this discussion. Complete coverage of this and other complex modeling problems are presented in literature referenced at the end of this chapter.

6.7 Redundancy and System Reliability

Redundancy provides a means for improving system reliability over that achievable by a nonredundant system. However, the advantages of redundancy can vary considerably depending on the particular redundant configuration used. Evaluation of the reliability of a redundant system configuration to provide the greatest reliability improvement involves the following:

a. Calculate the reliability of the original nonredundant configuration.

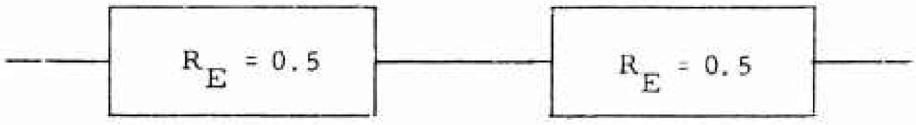
b. Inspect the reliability of each element in the nonredundant configuration to determine weak links where redundancy might prove beneficial.

c. Consider the various possible redundant element configurations.

d. Calculate and compare the reliability of each of the various redundant element configurations under consideration.

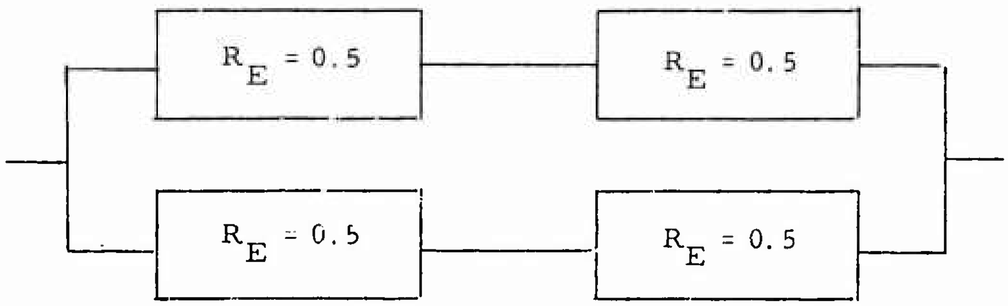
Any of the various types of redundancy discussed previously may be employed at any level within a system. The greatest gain in reliability is often realized when redundancy is applied at the lowest possible level. For example, compare the reliabilities obtained through each of the configurations in Figure 11 - 7. Each configuration represents an equipment consisting of two functional units having equal reliabilities. Configuration A is nonredundant, configuration B is redundant at the equipment level (high level redundancy), and configuration C is redundant at the unit level (low level redundancy). The reliability of configuration C is significantly

Configuration A



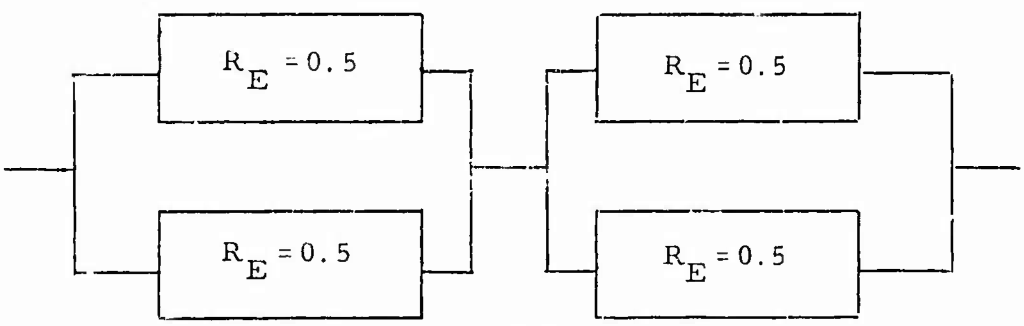
$$R_A = (0.5)^2 = 0.25$$

Configuration B



$$R_B = 1 - (1-(0.5)^2)^2 = 0.4375$$

Configuration C



$$R = [1-(1-.5)^2]^2 = 0.5625$$

Figure 11-7. Comparing Reliability of Various Configurations

higher than that of configuration B, even though each contain the same number of redundant elements. In addition, it is apparent that redundancy always involves a penalty in the form of increased weight, space, cost and usually, decreased maintainability. The decision to apply redundancy should only be made after detailed analysis to evaluate the reliability of each of the various redundant configurations under consideration, with respect to the weight and space requirements and cost of various alternative redundant design possibilities.

Decisions can then be made to introduce redundancy at the levels which will produce the greatest overall reliability improvement at least cost, and within the practical system limitations.

7. HUMAN FACTOR CONSIDERATIONS IN RELIABILITY IMPROVEMENT

The importance of considering human factors in reliability improvement becomes evident when system reliability is defined in terms of Operational Reliability rather than Hardware Reliability. AFR80-5 defines Operational Reliability as "....the probability that an operationally ready system will react as required to accomplish its intended mission....". This regulation further defines a complete system in terms of "....facilities, equipment, material, services, and personnel required for its operation....". Thus, an operational system includes a personnel subsystem to provide certain manipulative and decision-making functions that are essential in achieving the required operational reliability. Even in the operation of an "automatic" system, human performance is at least required to "push the button" and initiate hardware operation.

The importance of the human element to achieve operational reliability varies with the proportion of the system functions that require human performance, and the sensitivity of the system to human error. In many situations, complex actions on the part of the human are essential and highly critical due to the operational nature of the system. In such case, it is possible to provide features to "aid the operator, but mechanical means for replacing or substituting for the operator are not feasible. In other cases, operational requirements are such that the actions and reactions necessary are far beyond the limits of human capability.

Many actions can be performed by either man or machine but the relative reliability of the performance may influence the selection of method. Table XI-3 lists several types of actions that are usually more reliably performed by humans and other types of actions that are usually more reliably performed by machine. In a particular case, however, the most reliable performance of a specific action may not necessarily provide the most reliable performance of the total system. For example,

Table XI-3 Comparison of Human and Machine Capabilities

Human Actions More Reliable	Machine Actions More Reliable
Sensing presence of low-level physical, chemical and visible light stimulus	Sensing stimuli outside man's normal range of senses (x-ray, radio waves, ultrasonics, etc)
Recognizing and classifying unpredicted stimuli	Recognizing and classifying predictable stimuli
Detecting stimuli in presence of high "noise"	Monitoring pre-specified events, especially when occurrence is infrequent
Recognizing unpredictable, complex and varying patterns (speech, pictures, etc.)	Count or measure physical quantities
Solve varied and unpredicted problems	Perform mathematical computations and process quantitative information
Reason inductively and generally from observation	Perform repetitive action
Adapt decisions to new situations	Maintain rapid and consistent performance over extended periods of time
Make subjective estimates	Store large quantities of information of predictable classes or types
Store (remember) large quantities of unrelated or unpredictable events (however, memory deterioriates with time)	Rapid and accurate recall of large amounts of quantitative information
Rapid recall of qualitative information (however, accuracy of recall may be poor)	Exert physical forces of any magnitude in controlled manner, and over extended periods of time
Exert "one time" physical forces of limited magnitude that cannot be predicted in advance	

reliability improvement achieved by providing a servo mechanism to reduce certain manipulation errors could be nullified by the failure rate of the mechanism. In other cases, the gain in reliability may not be justified in view of the cost of the more reliable machine.

It is evident that system reliability is dependent, to a large extent on the effective application of human engineering principles. In fact, many of the reliability trade-off and allocation studies performed during system development involve significant human factor parameters.

7.1 Operational Reliability/Human Error Relationship

The relationship between human error and system reliability can be illustrated by defining an error as any action that will cause an out-of-tolerance condition to exist and, therefore, produce a system failure. Thus, the probability of human error is analogous to the probability of hardware failure in so far as operational reliability is concerned. The critical nature of human performance in relation to system operational reliability becomes evident when the personnel subsystem is considered effectively as a "series" element of the total system. In this context, personnel subsystem reliability can be defined as the probability of error-free operation over the required operating time period, and could be included as a multiplication factor in the total system reliability equation. Thus, the overall system reliability is limited by the reliability of the personnel subsystem.

7.2 Reliability Improvement Through Reduction Of Human Error

Engineering activities performed for the purpose of reducing human error and, thereby, improve operational reliability involve virtually all aspects of system design. This includes the obvious areas of operational controls and other items in the man-machine interface. However, other areas are also important considerations. For example, a maintenance error can result in a subsequent operational error. Therefore, certain aspects of maintainability design are also a part of the reliability improvement effort. In fact, all human engineering activities during system development have, as their ultimate objective the reduction of human error and, as such, are a part of reliability improvement.

The wide scope of associated activities precludes an in-depth discussion of human engineering techniques. However, the following list serves to summarize some of the human factor activities directed toward the reduction of human error and which are, therefore a part of reliability improvement.

a. Identification of Functions to be Fulfilled by the System. This includes an analysis to identify all functions that can conceivably be performed by human beings, even though some may also be considered for machine performance.

b. Performing trade studies where necessary for optimizing the allocation of various functions to human or machine operation.

c. For functions considered for human performance: performing analyses to define all associated operational requirements, and to identify and evaluate alternative devices to facilitate such operations. This includes displays, controls, and devices or techniques to aid the decision-making process.

d. Evaluating display requirements and establishing criteria such as:

- The most appropriate sensory modalities for receiving each type of information in question.

- Appropriate type of displays for providing information when and where needed, and in a manner that will insure reception. This can include consideration of factors such as display type, stimulus dimension and codes, and specific display features.

- Optimum display arrangement, both in relation to the user, and in relation to other displays and controls.

- Reasonable bounds for information inputs to assure compatibility with human information-receiving capacities.

- Time-sharing constraints to avoid degradation of information reception due to saturation of response capability.

e. Evaluating decision-making requirements to assure maximum reduction of decision errors by considering:

- Clarity of decisions that must be made in relation to the number of alternate choices, and the possibility of "predetermining" decisions in terms of specified conditions.

- Appropriate use of the human decision-making ability, including trade-off between cost of pre-programming and adoptive decision-making ability as means for responding to stimuli.

- Reduction of decisions to be made to the minimum, commensurate with system objectives.

f. Evaluating manual control requirements to assure reliable operation. This includes consideration of factors such as:

- Clarity and ease of identification of controls.
- Compatibility of operation of controls with respect to corresponding display and common human response tendancies.
- Suitability of control type for given requirements.
- Compatibility of operational requirements of control (force, speed, precision, etc.) and human capability.
- Arrangement of controls for optimum use.

g. In addition to the activities mentioned above, human engineering is also concerned with such factors as:

- Requirements of the communications network, if any, with regard to the burden placed on the individuals involved.
- Logical grouping of tasks to be performed.
- Requirements for time-sharing in performing tasks, especially during emergencies.
- Provisions for redundancies in the form of back-up personnel or machines.
- Training requirements imposed by the tasks to be performed.
- Compatibility between work aids and training aids.
- Training simulator requirements.
- Suitability of work space.
- Environmental conditions with regard to physical well-being of individuals.

7.3 Evaluating Personnel Subsystem Reliability Improvement

Recently, a method has been developed by which it is possible to evaluate the effect of man as a systems contributor.[1] Although developed initially to predict degradation resulting from the periodic maintenance performed on rocket engines, its value as a predesign tool in evaluation of personnel subsystem reliability is readily evident.

The technique derives mathematical relationships between quantified observations of small segments of human performance, in terms of reliability of task performance, and a judged or predicted value of a like segment of behavior utilizing similar hardware configurations applied to a specific condition. By combining the observed and the judged event into a mathematical relationship, it is possible to predict the reliability with which the human will perform a task and, ultimately, the contribution of the human element to system operation.

The above approach permits an analysis of man's function in a system, and a predictive measure applied to his performance. It provides the means whereby existing data may be extrapolated to conditions or procedures not previously observed or recorded for the purpose of "designing-in", or provisioning for, Human Factors solutions. The method is outlined as follows:

a. Identify the Tasks to be Performed. The tasks to be performance rated are identified at a gross level such that each task represents one complete operation, such as "perform functional check," or "prepare for engine leak check." Each task is made up of a series of sub-tasks which must be performed sequentially in order to complete the operation.

b. Identify the Task Elements. Once the major tasks have been identified each is broken down to the basic elements, or sub-tasks, necessary for task completion. As an illustration, the "prepare for engine leak check" task can be defined in terms of sub-tasks such as "connect hose," "rotate control valve," and "read gauge". Each task element involves a small segment of human performance that may be assessed in terms of probability of error. Further, evaluation of the sub-task permits application of the result to a number of seemingly different tasks, but which may, in fact, be composed of a number of similar sub-tasks.

---

[1] Annals of Reliability and Maintainability, Volume 4, July 1965.

c. Obtain Empirical Task Performance Data. Due to the elementary nature of the defined sub-tasks, it is possible to obtain empirical data concerning the reliability of task performance. For example, it is possible to devise tests that will be sensitive to errors in performing single tasks. Much data of this nature is available in the literature as a result of previous human factors studies. Such data are generally the result of controlled tests performed under laboratory conditions, however, and appropriate revisions to account for variations in the use environment are usually necessary.

d. Establish Sub-Task Rate. In order to arrive at element reliability, each sub-task to be considered is rated in accordance with its level of difficulty or error potential. "Rate" in this context, is the error potential with reference to the requirements of the gross task, the system or components on which the sub-tasks are to be performed, the level of skill of the technician on the job. The ratings derived for each task are statistically summarized, and a pooled rating are assigned to each element of work under evaluation.

e. Develop Regression Equation. In order to provide the means with which sub-task reliability may be predicted, the empirical data and the judged rating of that data are expressed in the form of a regression line, or equation, and tested for goodness of fit to describe the precision with which human performance reliability may be predicted.

As an example, a plot of the data from the original study took the form as shown in Figure 11- 8.

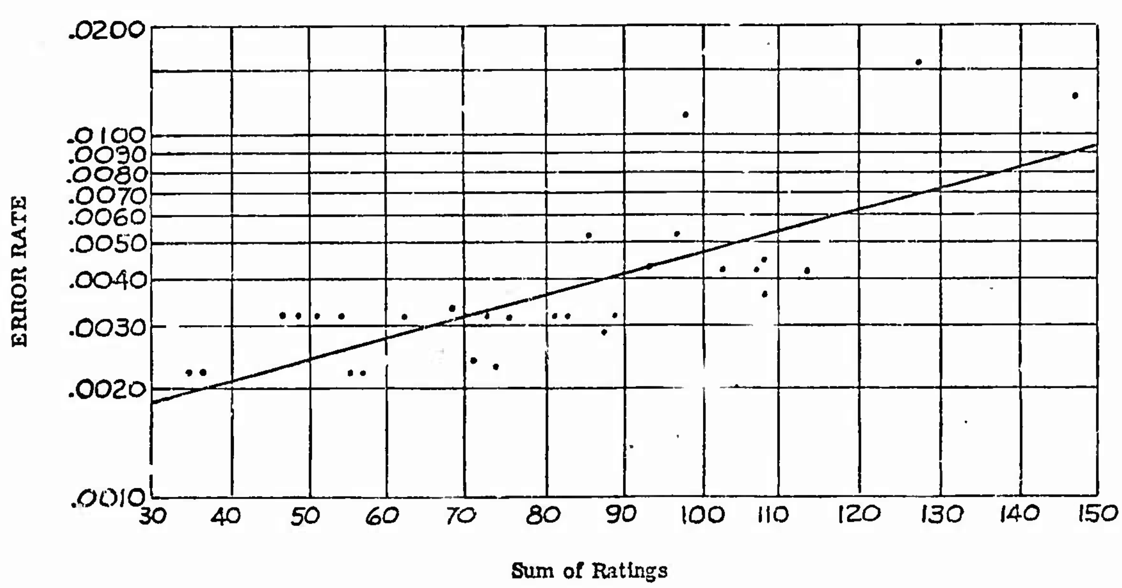


Figure 11-8. Error Rate vs. Error Potential Rating

The line that provided the best fit was found to be expressed in logarithmic form as:

$$\text{Log}\,E = -2.9174 + 0.006122R$$

where:

E = Error Rate
(Error Rate = 1-Empirical Reliability)

R = Pooled Ratings of Error Likelihood

The regression line, or equation, once developed, is utilized to provide sub-task reliability estimates for which there are no empirical data.

f. Establish Task Reliability. The sub-tasks are identified with specific tasks and reliability estimates are assigned to the sub-tasks as derived from the regression line previously developed. Based on established procedures, total task reliability is obtained as the product of the sub-task reliabilities which may further be combined to provide an estimate of the human contribution to component and system performance. Task element reliabilities as obtained in an original study are shown in Table XI-4. The method outlined is applicable to the evaluation of the performance of one person acting alone. However, where an element of operator or technician back-up is anticipated for some, or all, of the sub-tasks, it is necessary to account for the additional surveillance, or task redundancy, and, thereby consider the increase in task element reliability that would result.

8. REFERENCES

The following readily available publications contain detailed information on the reliability improvement techniques mentioned in this chapter, and are recommended for reference where more complete discussion of the subject is desired. Additional references are listed in Chapter 12.

(1) Reliability Stress and Failure Rate Data for Electronic Equipment, MIL-HDBK-217.

(2) Handbook, Reliability Engineering, NAVWEPS 00-65-502, 1 June 1964.

(3) Bureau of Ships Reliability Design Handbook, NAVSHIPS 94501.

TABLE XI-4. Means and Standard Deviations of Ratings and Reliability Estimates for the Task Elements *

Task Element	Rating Mean	Rating S.D.	Reliability Estimate	Task Element	Rating Mean	Rating S.D.	Reliability Estimate
Read technical instructions	8.3	2.2	.9918	Fill sump with oil	4.3	1.6	.9981
Read time (Brush Recorder)	8.2	2.1	.9921	Disconnect flexible hose	4.2	2.0	.9982
Read electrical or flow meter	7.0	2.8	.9945	Lubricate torque wrench adapter	4.2	2.2	.9982
Inspect for loose bolts and clamps	6.4	1.9	.9955	Remove initiator simulator	4.1	1.9	.9983
Position multiple position electrical switch	6.3	2.4	.9957	Install protective cover (friction fit)	4.1	2.2	.9983
				Read time (watch)	4.1	2.1	.9983
Mark position of component	6.2	2.1	.9958	Verify switch position	4.1	1.9	.9983
Install lockwire	6.0	2.3	.9961	Inspect for lockwire	4.1	2.1	.9983
Inspect for bellows distortion	6.0	2.7	.9961	Close hand valves	4.0	2.6	.9983
Install Marman clamp	6.0	1.8	.9961	Install drain tube	4.0	2.1	.9983
Install gasket	6.0	2.1	.9962	Install torque wrench adapter	3.9	1.7	.9984
Inspect for rust and corrosion	5.9	2.1	.9963	Open hand valves	3.8	2.6	.9985
Install "O" ring	5.7	2.2	.9965	Position tow position electrical switch	3.8	1.5	.9985
Record reading	5.7	2.3	.9966				
Inspect for dents, cracks and scratches	5.6	2.4	.9967	Spray leak detector	3.7	2.0	.9986
				Verify component removed or installed	3.5	2.4	.9988
Read pressure gauge	5.4	2.2	.9969				
Inspect for frayed shielding	5.4	2.3	.9969	Remove nuts, plugs and bolts	3.5	1.7	.9988
Inspect for QC seals	5.3	2.6	.9970	Install pressure cap	3.4	1.6	.9988
Tighten nuts, bolts and plugs	5.3	2.6	.9970	Remove protective closure (friction fit)	3.2	1.6	.9990
Apply gasket cement	5.3	2.3	.9971				
Connect electrical cable (threaded)	5.2	2.2	.9972	Remove torque wrench adapter	3.0	1.6	.9991
Inspect for air bubbles (leak check)	5.0	2.2	.9974	Remove reducing adapter	3.0	1.7	.9991
Install reducing adapter	4.9	1.6	.9975	Remove Marman clamp	3.0	1.7	.9991
Install initiator simulator	4.9	2.5	.9975	Remove pressure cap	2.8	1.8	.9992
Connect flexible hose	4.9	2.4	.9975	Loosen nuts, bolts and plugs	2.8	1.3	.9992
Position "zero in" knob	4.8	1.6	.9976	Remove union	2.7	1.4	.9993
Lubricate bolt or plug	4.7	2.7	.9977	Remove lockwire	2.7	1.5	.9993
Position hand valves	4.6	1.6	.9979	Remove drain tube	2.6	1.4	.9993
Install nuts, plugs and bolts	4.6	1.7	.9979	Verify light illuminated or extinguished	2.2	1.6	.9996
Install union	4.5	1.8	.9979				
Lubricate "O" ring	4.5	2.5	.9979	Install funnel or hose in can	2.0	0.8	.9997
Rotate gearbox train	4.4	2.0	.9980	Remove funnel from oil can	1.9	1.4	.9997

*These values were obtained from Annals of Reliability and Maintainability, Volume 4, July 1965.

(4) Morgan, Cook, Chapanis, Lund, Human Engineering Guide to Equipment Design, McGraw-Hill, New York, N. Y.

(5) Calabro, S. R., Reliability Principles and Practices, McGraw-Hill, New York, N. Y. 1962.

(6) Human Engineering Design Criteria for Aerospace Systems and Equipment, MIL-STD-803.

(7) AGREE Reliability of Military Electronic Equipment. Government Printing Office, Washington, D. C., 1957.

(8) Handbook For Systems Application Of Redundancy, U. S. Naval Applied Science Laboratory, 1966.

(9) RADC TR-67-292, Effectiveness of Display Subsystem Measurement and Prediction Techniques, Sept. 1967, AD 821142.

(10) An Index of Electronic Equipment Reliability, DATA STORE, AIR-C43-1/62-RP(1), 31 Jan. 1962, AD 607 161.

(11) RADC TR-1-66, Interference Notebook, Jan. 1966, AD 484585.

CHAPTER 12

RELIABILITY REFERENCES AND INFORMATION SOURCES

1. INTRODUCTION

Information and data concerning reliability program management and reliability engineering are readily available from a wide variety of sources and cover virtually all aspects of the reliability technology. Furthermore, the emphasis being placed on reliability by industrial and commercial organizations, as well as by the military and other government agencies, is resulting in a continuing increase in information and data.

As a result of the number of participants, the amount of information is vast and it would be impractical to present a complete listing of all reliability and data sources. However, this chapter is included to identify a number of readily available documents and references relating to the various subjects covered in the notebook. Also, some important sources of additional reliability data and information are identified at the end of the chapter.

2. MILITARY DOCUMENTS

Some of the important military documents relating to military reliability programs are listed below. This list, which references documents used by all branches of the service is presented for information purposes only, and is not intended to indicate Air Force policy in regard to documents imposed on Air Force contracts.

2.1 Military Standards

MIL-STD-721A, Definition of Terms for Reliability Engineering, 1962.

MIL-STD-756A, Reliability Prediction Procedure for Aircraft, Missiles, Satellites, and Electronic Equipment, 1963.

MIL-STD-810, Environmental Test Methods for Aerospace and Ground Equipment, 1962.

MIL-STD-105D, Sampling Procedures and Tables for Inspection by Attribute.

MIL-STD-414, Sampling Procedures and Tables for Inspection by Attribute.

MIL-STD-781A, Test Levels and Accept/Reject Criteria for Reliability of Nonexpendable Electronic Equipment.

MIL-STD-785, Requirements for Reliability Programs (for Systems and Equipments).

MIL-STD-690A, Failure Rate Sampling Plans and Procedures, 1965.

MIL-STD-790B, Reliability Assurance Program for Electronic Parts Specifications, 1966.

2.2 Military Specifications

MIL-Q-9858A, Quality and Inspection Program Requirements.

MIL-H-27894A(USAF), Human Engineering Requirements for Aerospace Systems and Equipment.

MIL-S-38130, Safety Engineering of Systems and Associated Subsystem and Equipment.

MIL-R-19610, General Specifications for Reliability of Production Electronic Equipment.

MIL-R-22732, Reliability Requirements for Shipboard and Ground Electronics Equipment.

MIL-R-22973, General Specification for Reliability Index Determination for Avionic Equipment Models.

MIL-R-23094, General Specification for Reliability Assurance for Production Acceptance of Avionic Equipment.

MIL-R-26484A, Reliability Requirements for Development of Electronic Subsystem for Equipment.

MIL-R-26667, General Specification for Reliability and Longevity Requirements, Electronic Equipment.

MIL-R-27173, Reliability Requirements for Electronic Ground Checkout Equipment.

2.3 General Use Military and DOD Publications

AFSCM/AFLCM 310-1 , Management of Contract Data and Reports.

AFSCM 375-1, Configuration Management During Definition and Acquisition.

AFSCM 375-4, System Program Management Procedures

AFSCM 375-5, Systems Engineering Management Procedures

AFM 66-1, Maintenance Management

MIL-HDBK-217A, Reliability Stress and Failure Rate Data for Electronic Equipment.

NAVSHIPS 94501, Bureau of Ships Reliability Design Handbook.

NAVSHIPS 94324, Maintainability Design Criteria Handbook for Designers of Shipboard Electronic Equipment.

H108, Sampling Procedures for Life and Reliability Testing (Based on Exponential Distribution). Department of Defense, Government Printing Office, Washington D. C., 1961.

TR-3, Sampling Procedure and Tables for Reliability and Life Testing Based on the Weibull Distribution (Mean Life Criterion), Office of the Assistant Secretary of Defense (Supply and Logistics) Washington, D. C., 1961.

TR-4, Sampling Procedures and Tables for Life and Reliability Testing Based on the Weibull Distribution (Hazard Rate Criterion), Office of the Assistant Secretary of Defense (Supply and Logistics), Washington, D. C., 1962.

3. COMMERCIALLY PUBLISHED REFERENCE BOOKS

The following recently published reference books and texts are representative of the many books presently available to the reliability program manager and reliability engineer.

ARINC Research Corporation, Reliability Engineering, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1964.

R. E. Barlow and F. Proschan, Mathematical Theory of Reliability, John Wiley & Sons, Inc., New York, 1965.

I. Bazovsky, Reliability Theory and Practices, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1961.

S. R. Calabro, Reliability Principles and Practices, McGraw-Hill Book Company, New York, 1962.

D. N. Chorafas, Statistical Processes and Reliability Engineering. D. Van Nostrand Co., Inc., Princeton, N.J., 1960.

E. L. Grant, Statistical Quality Control, 3rd Ed., McGraw-Hill Book Company, New York, 1964.

G. J. Hahn, S. S. Shapiro, Statistical Models in Engineering. John Wiley & Sons, Inc., New York, N.Y., 1967.

D. R. Lloyd, M. Lipow, Reliability: Management, Methods and Mathematics, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1962.

R. H. Myers, K. L. Wong, H. M. Gordy (eds.) Reliability Engineering for Electronic Systems, John Wiley & Sons, Inc., New York, 1964.

E. Pieruschka, Principles of Reliability, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1963.

G. H. Sandler, System Reliability Engineering, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1963.

R. L. Wine, Statistics for Scientists and Engineering, Prentice-Hall, Inc., Englewood Cliffs, N.J.

4. SPECIALIZED REFERENCES

The articles and publications referenced below provide specialized information and data relating to various subjects discussed in this notebook. These references are grouped according to general subject.

4.1 Reliability Program Management

L. W. Ball, Reliability Management by Objectives and Results, Proceedings, Eighth National Symposium on Reliability and Quality Control, 1962, pp. 156-162.

L. W. Ball, Management Policies for Assigning Departmental Reliability Responsibilities, Industrial Quality Control, ASQC, Vol. 17, April 1961, pp. 16-19.

V. J. Bracha, Analysis of Reliability Management in Defense Industries, BSD-TDR-62-48, June 1962.

E. F. Dertinger, Funding Reliability Programs, Proceedings, Ninth National Symposium on Reliability and Quality Control, 1963, p. 16.

W. R. Kuzmin, Rework Costs Related to Reliability Requirements, Proceedings, Sixth National Symposium on Reliability and Quality Control, 1960, p. 95.

H. C. Romig, PERT-PEP Reliability Controls Techniques Simplified, Proceedings, Eighth National Symposium on Reliability and Quality Control, 1962.

R. W. Smiley, Military Management of Missile Quality Control Programs, Proceedings, Ninth National Symposium on Reliability and Quality Control, 1963.

4.2 Reliability Assurance

C. J. Brzesjinski, Reliability Assurance Provisions in Specifications, Industrial Quality Control, Vol. 18, No. 10, April 1962, pp. 9-11.

E. J. Brieding, Purchasing Reliability, IRE Transactions on Reliability and Quality Control, Vol. RQC-9, April 1960, pp. 19-22.

C. C. Peterson, Specification and Assurance of Large MTBF's Typical of Spacecraft Electronic Equipments, Military Systems Design, April 1963, pp. 27-33.

A. R. Park. Reliability Through Adequate Specification, Fifth National Symposium on Reliability and Quality Control, January 1959, pp. 246-250.

R. L. Landers. Reliability and Product Assurance, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963.

ARINC Research Corporation, The Allocation of System Reliability, Publication 152-2-274, November 1961.

A. P. Basu, Estimates of Reliability for Some Distributions Useful in Life Testing, Technometrics, Volume 6, p. 215, 1964.

H. L. Harter, Some Aspects of Reliability and Life Testing, Electronics Division ASQC, Volume 3, No. 1, p. 5, 1964.

G. R. Herd, Some Statistical Concepts and Techniques for Reliability Analysis and Prediction, Proceedings, Fifth National Symposium for Reliability and Quality Control, 1959.

4.3 Reliability Achievement

B. J. Flehinger, Reliability Improvement Through Redundancy at Various Systems Levels, IRE National Convention Record, Part 6, 1958.

F. Proschan, F. A. Bray, Optimism Redundancy Under Multiple Constraints, Office of Technical Services, Washington, D.C., May 1963, AD-408393.

F. E. Dreste, Circuit Design Concepts for High Reliability, Proceedings, Sixth National Symposium on Reliability and Quality Control, January 1960, pp. 121-133.

L. A. Aroian, R. H. Meyers, Redundancy Considerations in Space and Satellite Systems, Proceedings, Seventh National Symposium on Reliability and Quality Control, 1961.

L. A. Aroian, The Reliability of Serial Systems and Redundant Systems, Proceedings, Tenth National Symposium on Reliability and Quality Control, 1964.

I. A. Lesk, Reliability Considerations in Microminiaturization, NAREM Record, Northeast Electronics Research and Engineering Meeting, IEEE, November 1964.

T. B. Lewis, Techniques for Achieving Operational Reliability and Maintainability in Digital Computer. Proceedings, Fifth National Convention Military Electronics, 1961.

5. SOURCES OF RELIABILITY DATA AND INFORMATION

Table XII-1 lists a number of Government agencies and technical and professional societies from which up-to date reliability information and data can be obtained.

Table XII-1. Reliability Data and Information Sources

Name and Address	Acronym or Other Identification	Comments
. Air Force Engineering and Logistics Information Systems. HQ-AFLC Wright-Patterson AFB Dayton, Ohio	. AFELIS . USAF Parts Data Bank	. Collects, stores, and provides rapid retrieval of data on reliability and availability of parts fulfilling stated requirements. . Responds to inquiries.
. Advisory Group on Electron Devices 346 Broadway New York City 10013	. AGED (Formerly AGEP and AGET)	. Proposes, monitors, and reports on state-of-the-art advancement projects on electron parts and tubes. . Issues annual and interim survey reports. . Answers status inquiries from qualified requesters. . Sponsored by Office of Director of Defense, R&E, DOD.
. Air Force Materials Laboratory Research and Technology Division (MAAE) Air Force Systems Command Wright-Patterson AFB Dayton, Ohio		. Generates, collects, and makes available data on the mechanical, physical, and thermophysical properties of material. . Publishes related reports and handbooks.
. Canadian Military Electronics Standards Agency.	. CAMESA	. Canadian parallel to DESA except large portion of testing is done [illegible] . Qualification data on: - Canadian Branches of U. S. Firms - Canadian Firms - U. S. Products
. Ceramic and Graphite Technological Evaluation Section. R&D Division Wright-Patterson Air Force Base Dayton, Ohio		. Processes, analyzes, and disseminates technical information on ceramics and graphite.

Table XII-1 Continued

Name and Address	Acronym or Other Identification	Comments
. Chemical Propellant Information Agency	. CPIA (Formerly LPIA and SPIA)	. Gathers performance data on liquid propellants, motors and components. . Gathers performance data on solid fuels, casings, and motor parts. . Distributes abstracts on reports to qualified recipients.
. Defense Atomic Support Agency Data Center. GE/Tempco Division Santa Barbara, California	. DASA Data Center	. Collects from and distributes to government and contractor locations Specific reliability program: Transient Radiation Effects on Electronics Systems (TREES).
. Defense Documentation Center Cameron Station, Building 5 5010 Duke Street Arlington, Virginia 22314	. DDC (Formerly ASTIA)	. Master center for all technical data generated on government contracts . Includes R&D, systems data, logistics. . Technical Abstracts Bulletin (TAB) issued twice monthly. . Government contractors can obtain reports within their designated field of interest without charge. . Some complex computerized search is possible.
. Defense Electronics Supply Agency Arlington, Virginia	. DESA	. Issues official qualified products lists showing companies demonstrating compliance with given MIL specifications. . Electronic Parts Function is under DESC-E, Gentile AFB, Dayton, Ohio.
. Defense Metals Information Center Battle Memorial Institute Columbus, Ohio	. DMIC	. Collects, processes, and disseminates technical information on structural metal and closely related aerospace materials. . Data on titanium, beryllium, magnesium, tungsten, molybdenum, columbium, etc.

Table XII-1 Continued

Name and Address	Acronym or Other Identification	Comments
. Division of Technical Information Extension U. S. Atomic Energy Commission P.O Box 62 Oak Ridge, Tennessee 37831	. DTIE	. AEC counterpart of DDC. . Publish semimonthly Nuclear Science Abstracts - Available from: Government Printing Office, Washington, D.C., 20402.
. Electronic Components Reliability Center Battle Memorial Institute Columbus, Ohio	. ECRC . See also MCRC	. Tabular summaries of parts tests contributed by members. . Services rendered under annual fee. . Provide special search services. . Consultation on parts problems.
. Electron Devices Data Service Electron Devices Section National Bureau of Standards Washington, D. C. 20234	. EDDS	
. Electronic Properties Information Center Hughes Aircraft Culver City, California	. EPIC	. Prepares and distributes evaluated data on electronic properties of aerospace material. . Sponsored by USAF/AFSC/ASD Materials Laboratory (See also REIC, MPIC, PLASTEC).
. Failure Rate Data U.S. Naval Ordnance Laboratory (Code 60) Corona, California	. FARADA	. Compiles failure-rate data into the Failure Rate Data Handbook. . Available to participants in FARADA program.
. Groth Institute Florida Atlantic University Boca Raton, Florida		. Collects, correlates and interprets data on physical and chemical properties of crystals.

Table XII-1 Continued

Name and Address	Acronym or Other Identification	Comments
. Interservice Data Exchange Program - Army Office: Army Missile Command Huntsville, Alabama - Navy Office: Officer-in-Charge (Code E-6) U.S. Naval Fleet Missile Analysis and Evaluation Group Corona, California 91720 - Air Force Office Aerospace Corporation, For: AFSSD El Segundo, California	. IDEP	. Exchange of summary and full test of parts-tests reports. . Services 150 participating contractors of the thru services and NASA. . Contact points for follow-on inquiries are identified at all participants.
. Inter-NASA Data Exchange Headquarters, NASA Washington, D.C.	. INDEX	. Detailed and justified Qualified Parts Listings for NASA use. . Failure rates, and performance data, compiled from many sources including vendor data. . This was a portion of NASA Preferred Parts and Sources Program.
. Mechanical Components Reliability Center Battelle Memorial Institute Columbus, Ohio	. MCRC	. Tabular summaries of mechanical parts test data. . Counterpart of ECRC.
. Mechanical Properties of Material Information Center Balfour Engineering Suttons Bay, Michigan	. MPIC	. Prepares and distributes evaluated data on strength of aerospace materials. . Air Force/ASD sponsored. (See also EPIC, REIC, PLASTEC.)

Table XII-1 Continued

Name and Address	Acronym or Other Identification	Comments
. Office of Standard Reference Data National Bureau of Standards Connecticut Ave. and Van Ness St., N.W. Washington, D.C. 20234		. Compiles and critically evaluates quantitative data on physical and chemical properties of substances.
. Scientific and Technical Information Division Code ATSS Washington, D.C. 20546	. NASA	. Central services for NASA, their contractors, and other government agencies-aerospace topics. . Performs searches and prepares bibliographies. . Issues STAR semimonthly; abstracts technical articles (also available from GPO). . Contracts with Research Triangle Abstracts and Technical Reviews. . Details available from NASA, Code KR.
. National Referral Center for Science and Technology Library of Congress Washington, D.C. 20450		. Refers inquiries to the location(s), information center, or individual most likely to be qualified to answer.
. National Federation of Science Abstracting and Indexing Services.	. NFSAIS	. Forum of nonprofit and government agencies working to achieve more uniformity among overlapping services. . Sponsored by National Sciences Foundation.
. Office of Technical Services U. S. Department of Commerce Washington, D. C. 20230	. OTS	. Collects and organizes technical reports resulting from government-financed research (available from GPO). . Cooperates with Science and Technical Division, Library of Congress to perform extensive literature searches (see basis). . Issues several indexes available or subscription (full catalog of government publications, selected government publications, technical translations, research reports, etc.). . Address inquiries to: Superintendent of Documents Goverments Printing Office, Washington, D.C. 20402

Table XII-1 Continued

Name and Address	Acronym or Other Identification	Comments
. Plastics Technical Evaluation Center Picatinny Arsenal Dover, New Jersey	. PLASTEC	. Collects, exchanges, collates, develops, and evaluates technical data on plastics of interest to DOD, with emphasis on structural, electrical, electronic, packaging, and rocket (missile applications).
. Prevention of Deterioriation Center National Academy of Sciences 2101 Constitution Avenue Washington, D.C. 20418		. Information on natural and induced environmental effects on materials and equipment. . Consulting service free to its sponsors, NASA, and U.S. Army Biological Laboratories and their contractors.
. Parts Reliability Information Center Code R-ASTR-TR Marshall Space Flight Center Huntsville, Alabama 35812	. PRINCE	. Computerized storage and periodic printout into an index of reliability test data pertinent to NASA requirements. . Available to NASA and approved contractor personnel. . Automatic advisement on new material to personnel qualifying for Field-of-Interest Register.
. Reliability Analysis Central . Rome Air Development Center Rome, New York	. RADC	. Collects and stores reliability data on microelectronic devices and semiconductor transistors and diodes.
. Radio Systems Division National Bureau of Standards South Broadway Boulder, Colorado 80301		. Reliability and efficiency of radio-spectrum use. . Standards of measurement in radio systems. . Consulting on a no-charge or contract basis depending on the size of the task.
. Reliability-Value Engineering Branch Engineering Division Assistant Chief for Research, Development, Test and Evaluation Bureau of Naval Weapons Washington, D. C.		. Information on methods of assigning reliability objectives to electronic and mechanical equipment. . Services available to government agencies and qualified contractors.

Table XII-1 Continued

Name and Address	Acronym or Other Identification	Comments
. Radiation Effects Information Center Batteile Memorial Institute Columbus, Ohio	. REIC	. Collects, analyzes, and distributes radiation-effects information on aerospace materials. . USAF/ASD funded. . Literature searches, answers to technical questions, and data compilation on request.
. Secretariat of Electronic Test Equipment New York University New York City	. SETE	. Compiles varied vendor claims into organized data. . Government funded, Air Force administered agency. . Furnishes information on test equipment.
. Shock and Vibration Centralizing Agency U.S. Naval Research Laboratory Code 1020 Washington, D. C. 20390		. Information on shock vibration, pressure, temperature and radiation.
. Technical Information Office Office of Naval Research Washington, D. C.	. TIO	. Directs property detailed requests for information to the proper channels within the ONR for possible answers.
. Thermophysical Properties Research Center Purdue University School of Mechanical Engineering Lafayette, Indiana	. TPRC	. Research and literature surveys on thermophysical properties of all substances. . Annual Publication: Retrieval Guide to Thermophysical properties Research Literature.

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13. ABSTRACT

RADC Reliability Notebook, Vol. I, is an updating of the RADC Reliability Notebook which was first published in 1958 and which had been revised several times up until the fall of 1966. This updating has resulted in a completely updated (except for Section 8) notebook in arrangement, format and material as per the contract under which the effort was conducted. There are 12 chapters comprising first a general discussion, followed by a presentation of information which project managers and project engineers can use to be more effective in predicting, measuring and improving system and equipment reliability. A subject index has been included at the end in order to provide the user with a guide to locating specific information.

This updating was based on a major collection of existing information with emphasis on reliability in large system development as well as in non-system or off-the-shelf hardware procurement programs. Emphasis has been placed on prediction techniques; test demonstration plans and analysis of test data; and on the relationship between reliability and various other factors including engineering disciplines, program milestones, design reviews and engineer/acceptance tests covered at length in various AF documents such as AFSCM/AFLCM 310-1 and the AFSCM 375 series of publications. Of particular significance is the inclusion of information on Bayesian statistics and the application of this statistical concept to the development of demonstration test plans and the interpretation of test data.

The information presented in this updated version of the RADC Reliability Notebook,

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Operational Reliability						
System Reliability Program						
Reliability Prediction						
Reliability Demonstration Test						
Reliability Program Management						

ABSTRACT CONT'D

together with the references and the guidelines contained in AF program management publications, will provide project engineers and project managers with a sound basis for implementing reliability oriented effort and program plans and for monitoring to insure that reliability objectives will be met.

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